From Molecular Clouds to Massive Stars

Star Formation in Numerical Simulations

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Collaborators:
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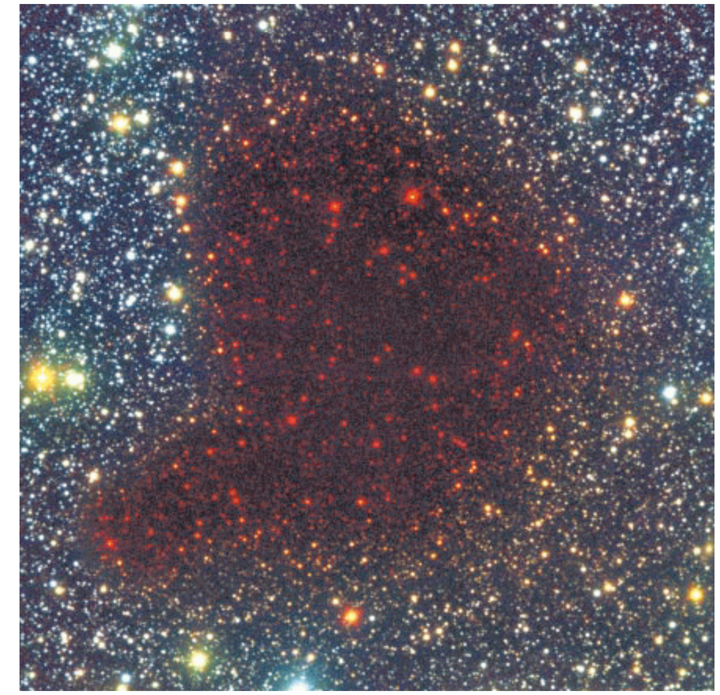
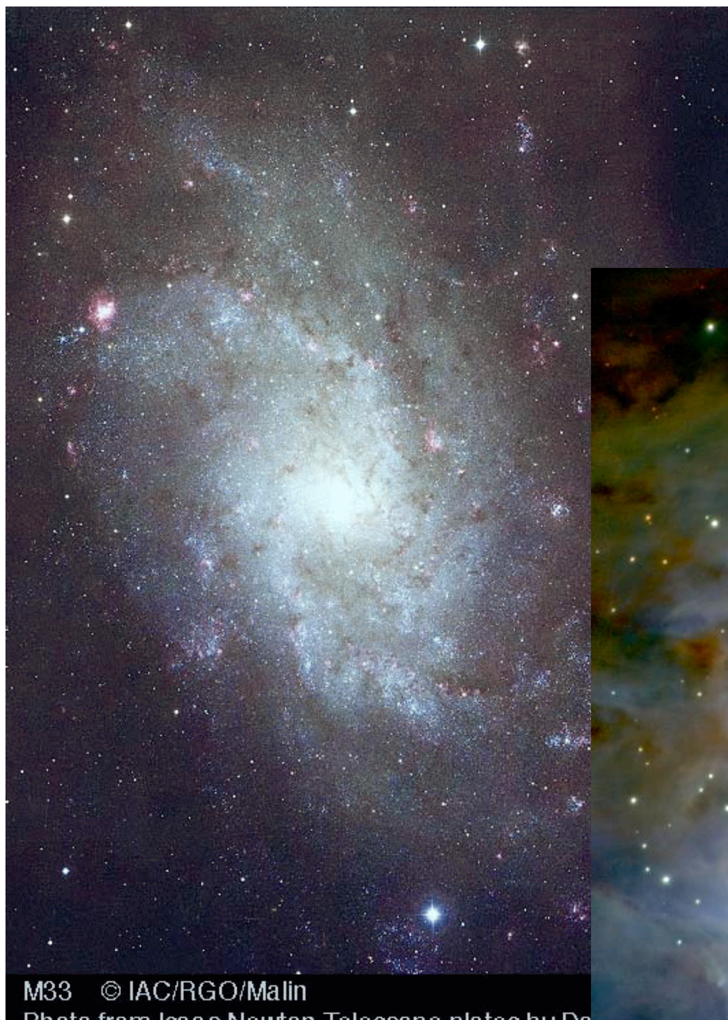
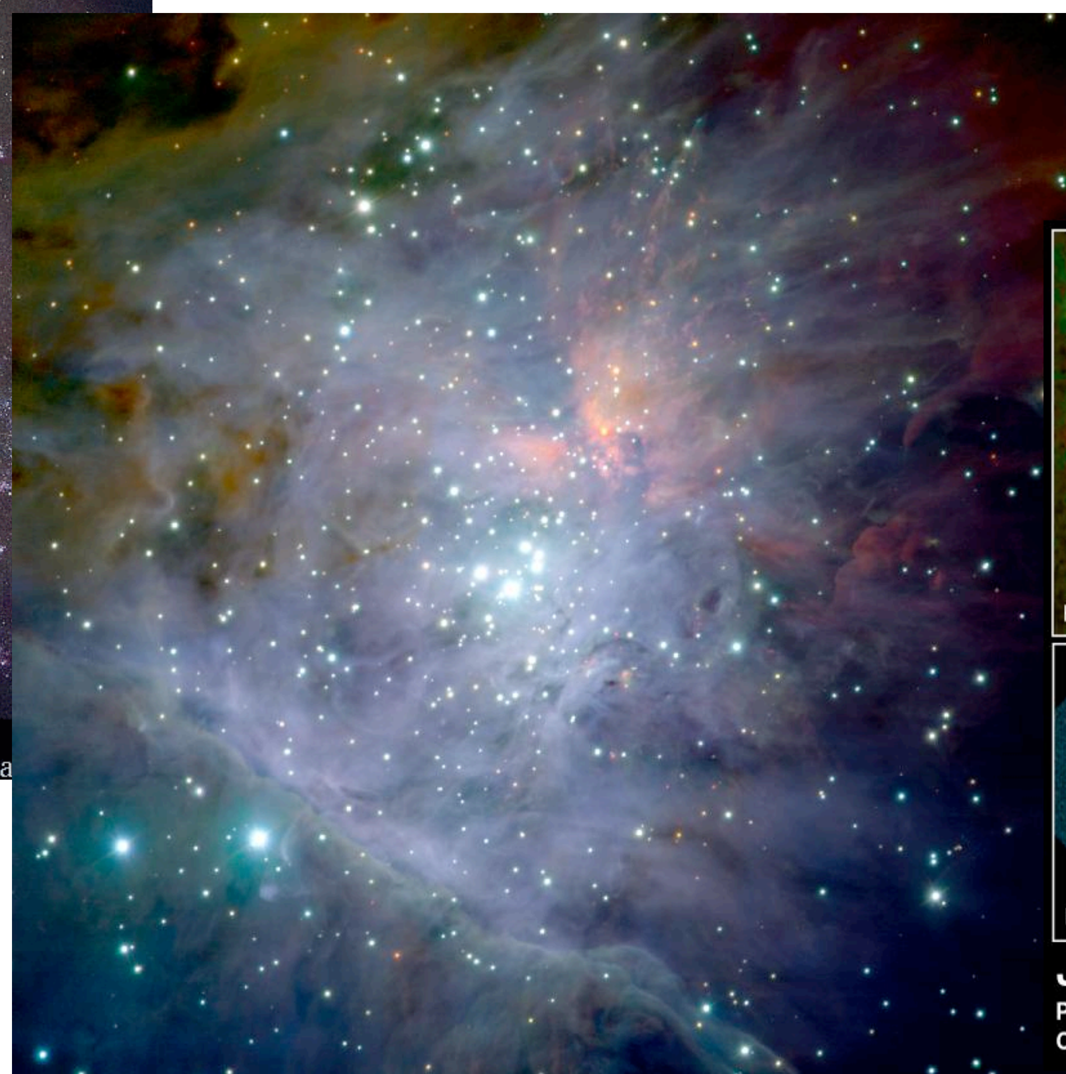
Patrick Hennebelle (ENS), Eric Keto (CfA)

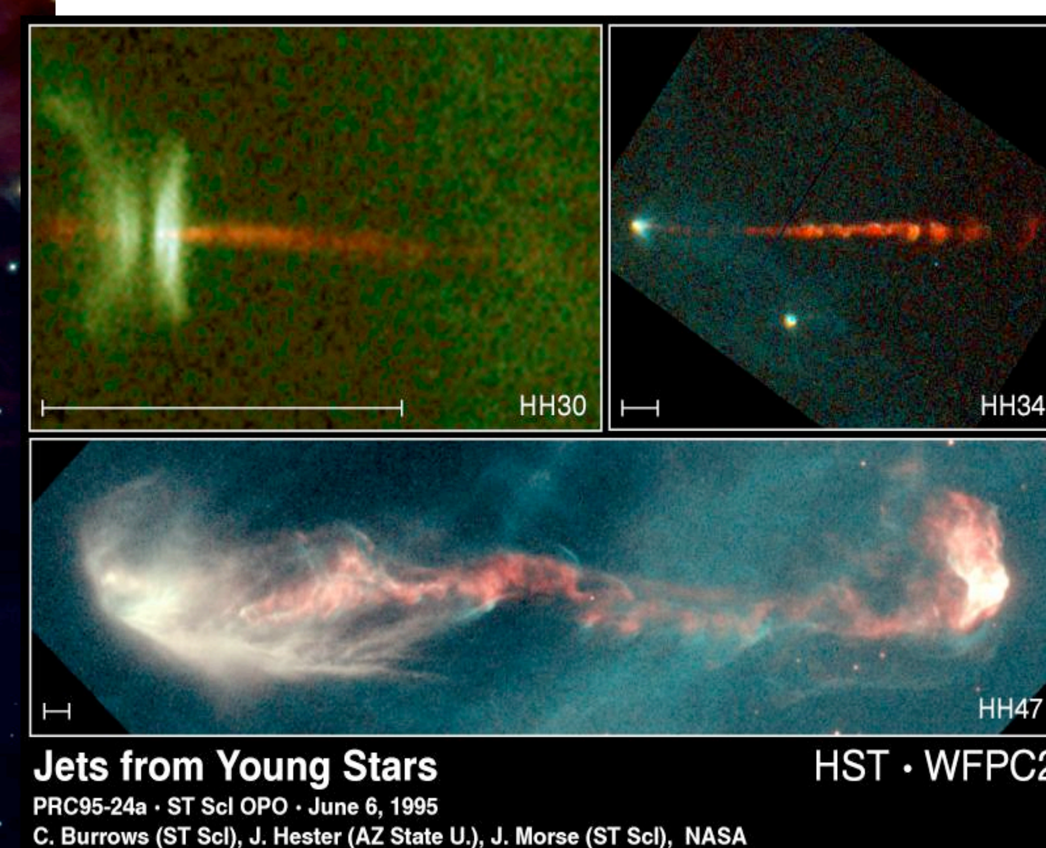
Motivation

Complexity of physical processes (gravity, turbulence, feedback) requires numerical simulations to study star formation







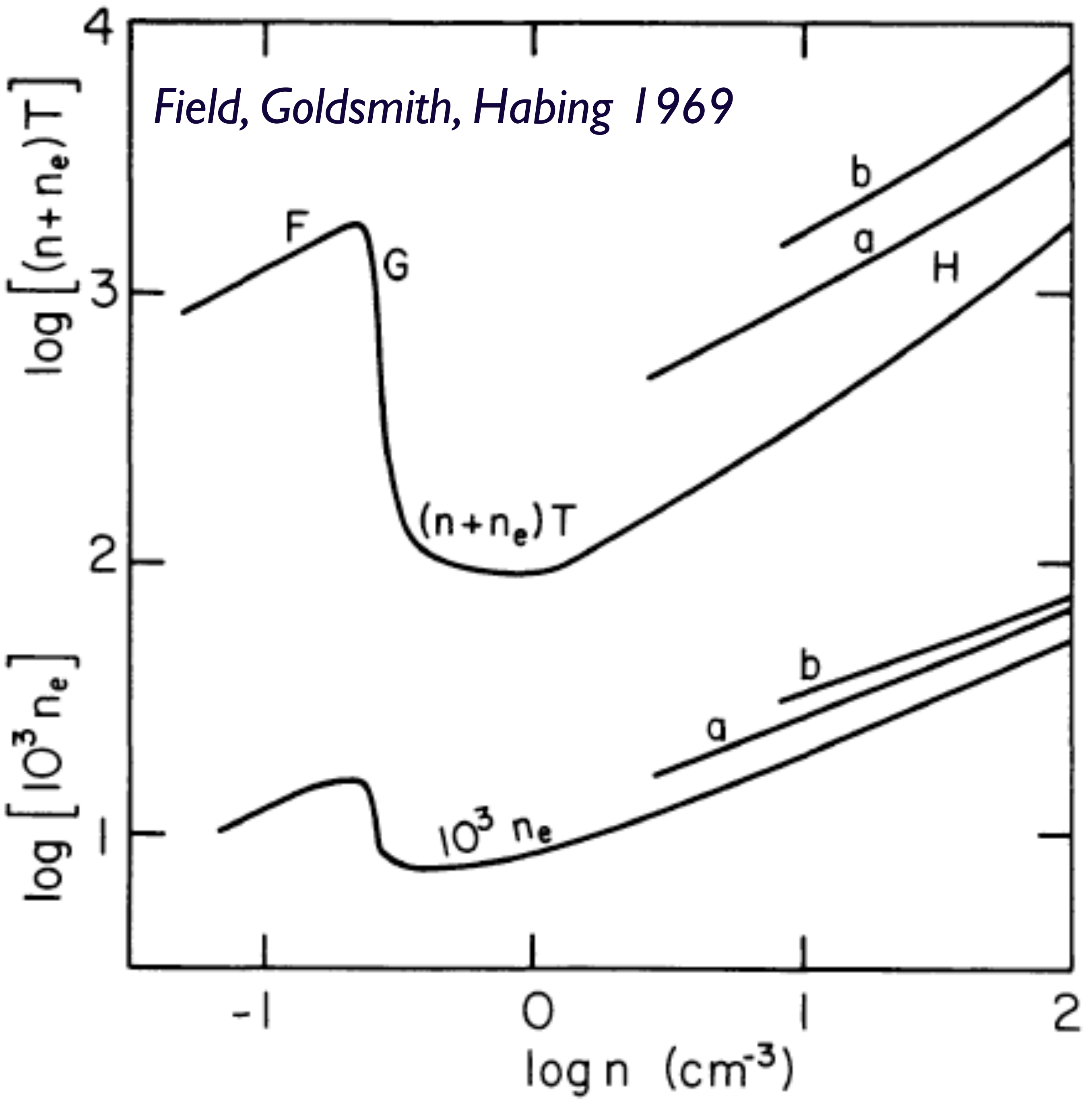


Formation of Molecular Clouds

- ISM: warm ionized gas, warm atomic gas, cold molecular gas, dust
- Irregular, inhomogeneous distribution
- highly turbulent
- magnetized
- Present day star formation happens in Giant **Molecular Clouds**
- properties of GMC: density ~10^{2-3} cm^{-3}, size ~ tens pc, mass ~ 10^{4-6} Msol
- composition: 70% hydrogen, 1% dust (mass)
- e.g. nearby Orion nebula (d ~ 400 pc)

Thermal Instability

Formation of dense, cold clouds out of the warm medium through thermal instability (*Field 1965*)?



$$\frac{\partial \ln p}{\partial \ln \rho} < 0$$ necessary condition for TI

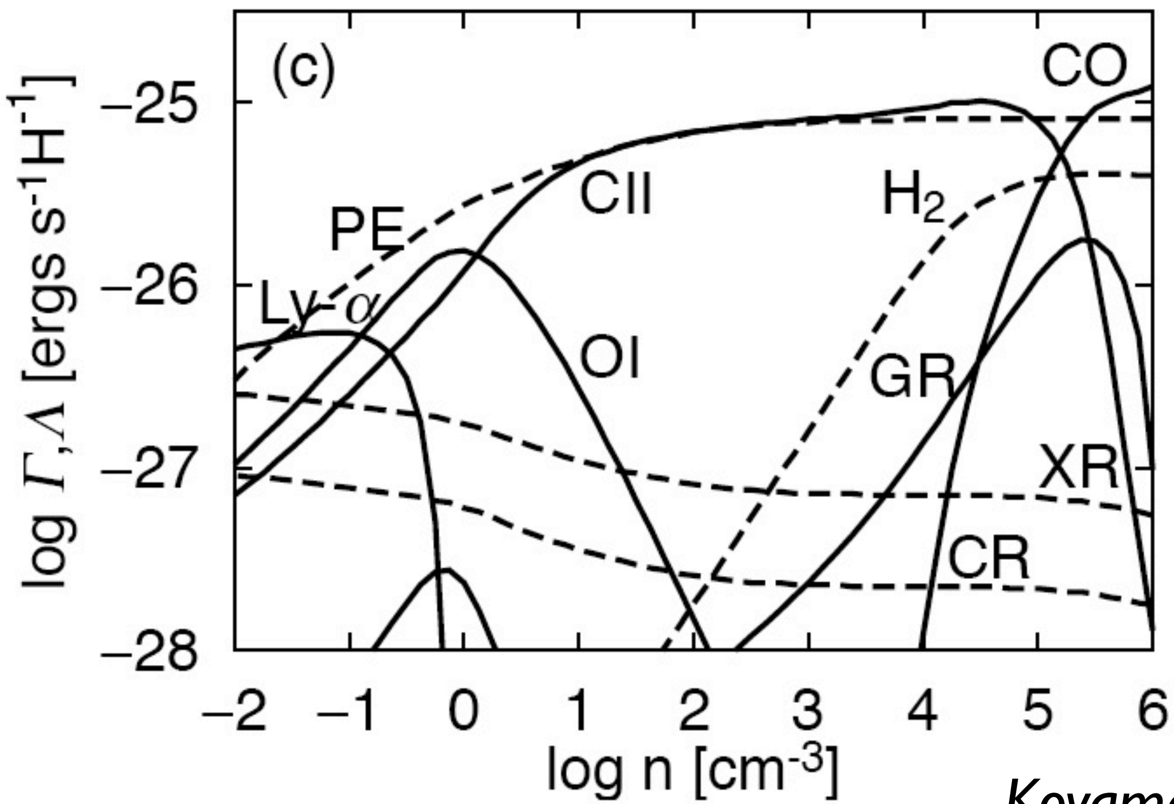
heating (UV, cosmic ray) and cooling (atomic and molecular line emission, gas-dust coupling) regulate thermodynamics

Note:

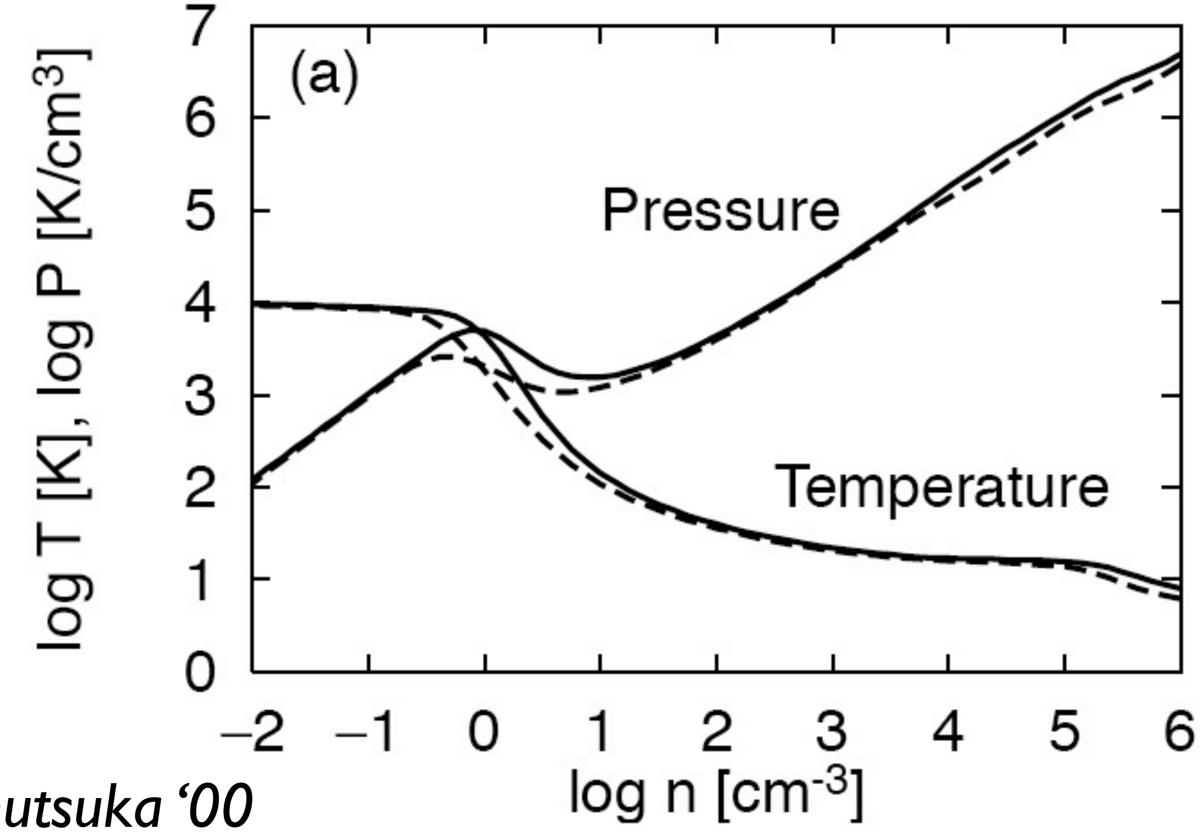
M_{Jeans}(warm gas) >> M_{cloud}

Thermal Instability

main cooling & heating processes



equilibrium pressure / temperature



Koyama & Inutsuka '00

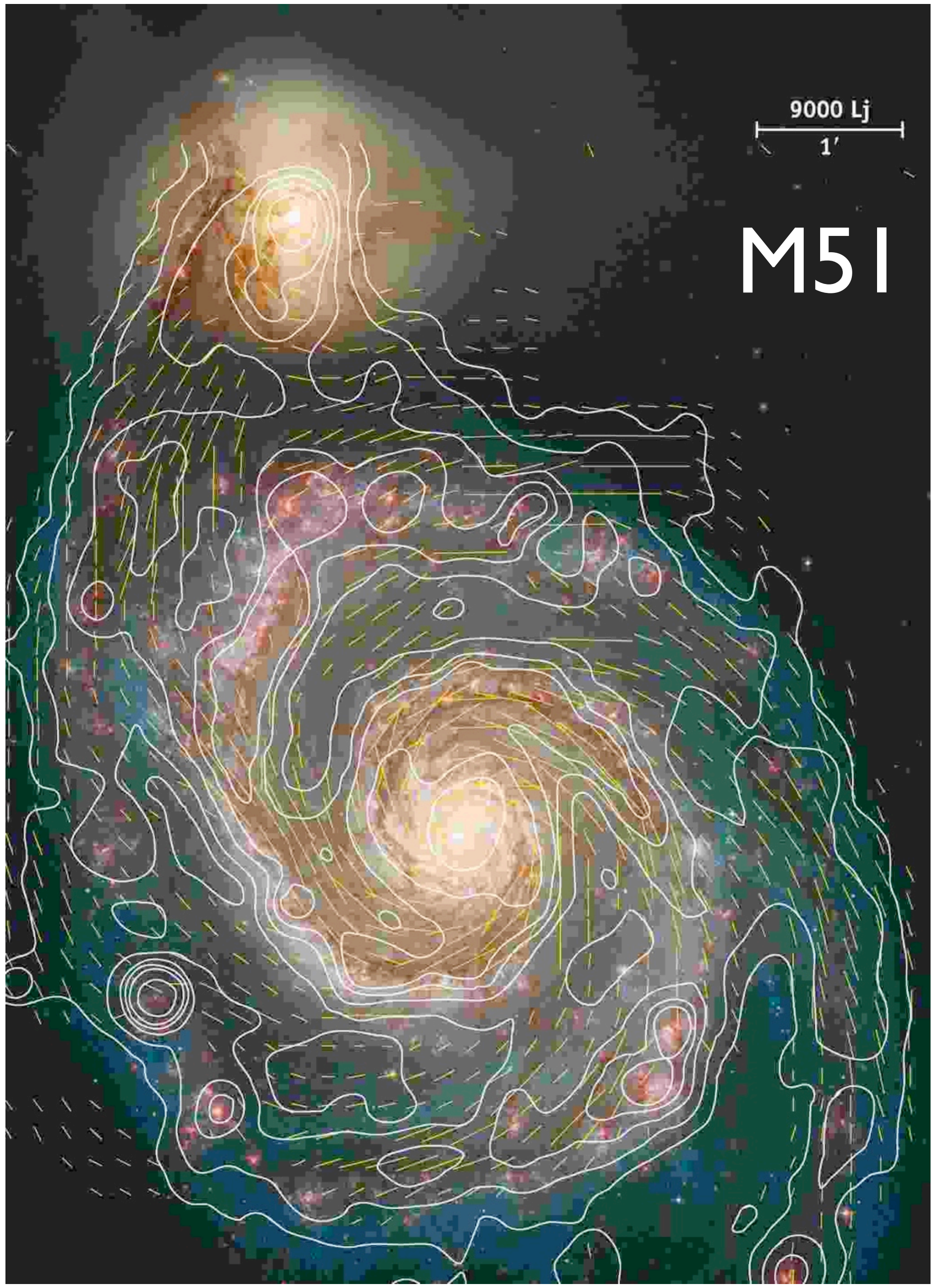
simplification:

$$\Gamma = 2.0 \times 10^{-26} \text{ ergs}^{-1},$$

$$\frac{\Lambda(T)}{\Gamma} = 10^7 \exp\left(\frac{-1.184 \times 10^5}{T + 1000}\right) + 1.4 \times 10^{-2}\sqrt{T} \exp\left(\frac{-92}{T}\right) \text{ cm}^3$$

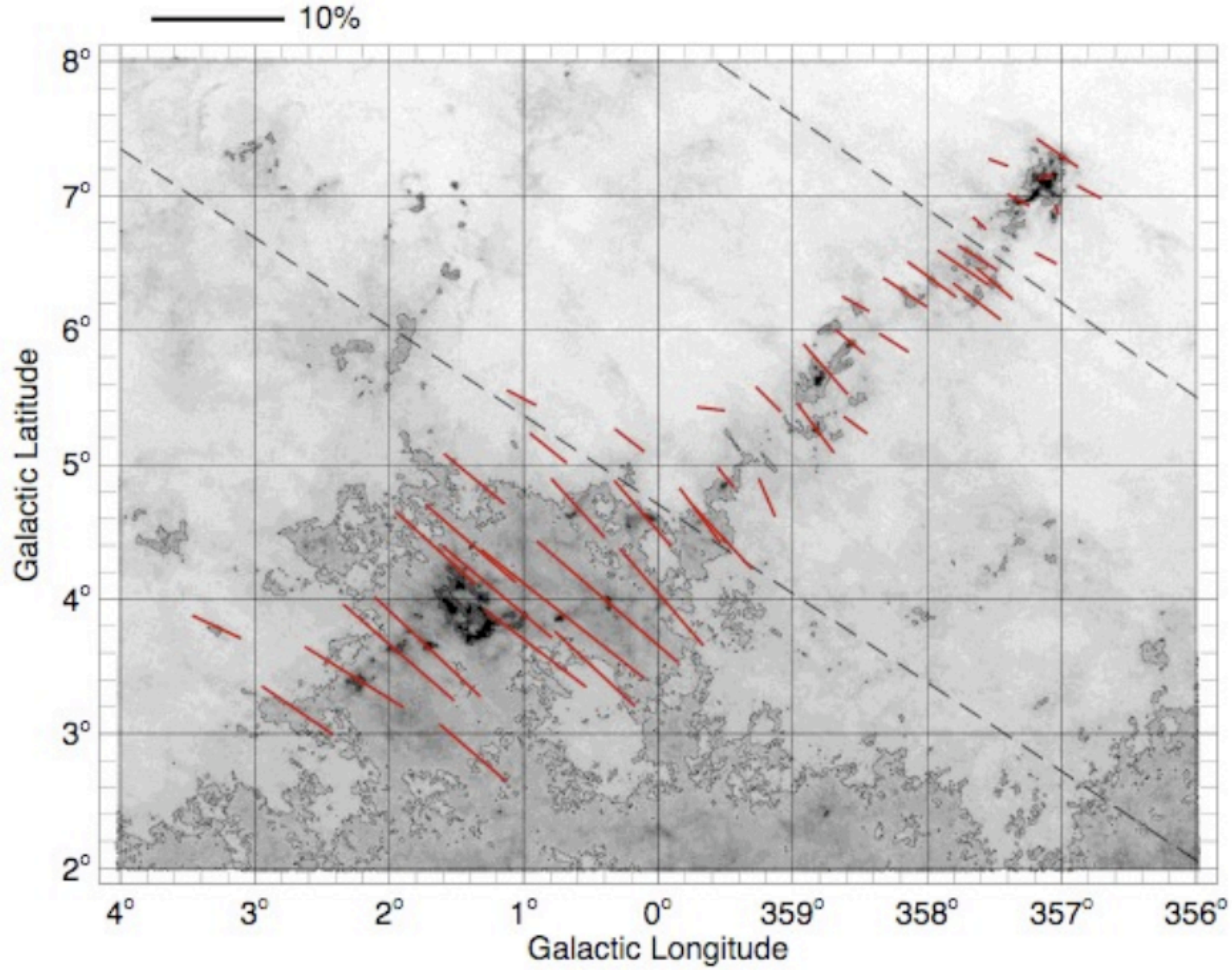
Koyama & Inutsuka '02

Magnetic Fields



galactic B-fields (e.g. *R.Beck 2001*)
large scale component: ~ 4μG
total field strength: ~ 6μG

The ISM is permeated with magnetic fields



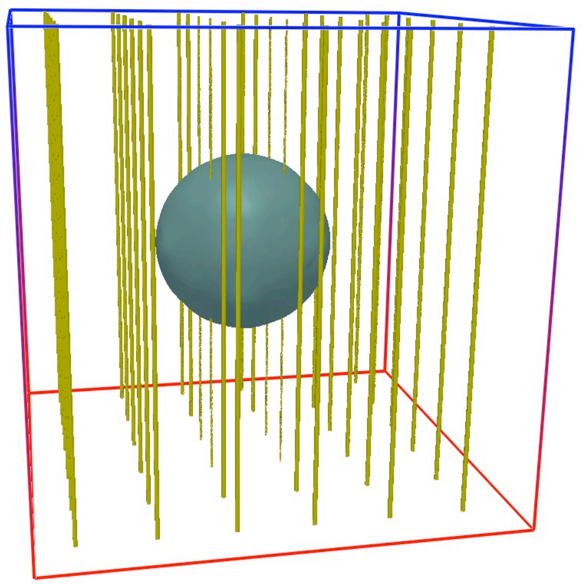
magnetic polarization measurements in the Pipe nebula
F.O.Alves, Franco, Girart 2008

Magnetic Fields

magnetic criticality

mass-to-flux ratio:

$$\mu \equiv \left(\frac{M}{\Phi}\right)$$ = self-gravity / magnetic support



critical value:

$$\mu_{\rm crit} = \frac{1}{2\pi\sqrt{G}} \approx 0.16/\sqrt{G}$$

uniform disc
Nakano & Nakamura 1978

$$\mu_{\rm crit} = 0.13/\sqrt{G}$$

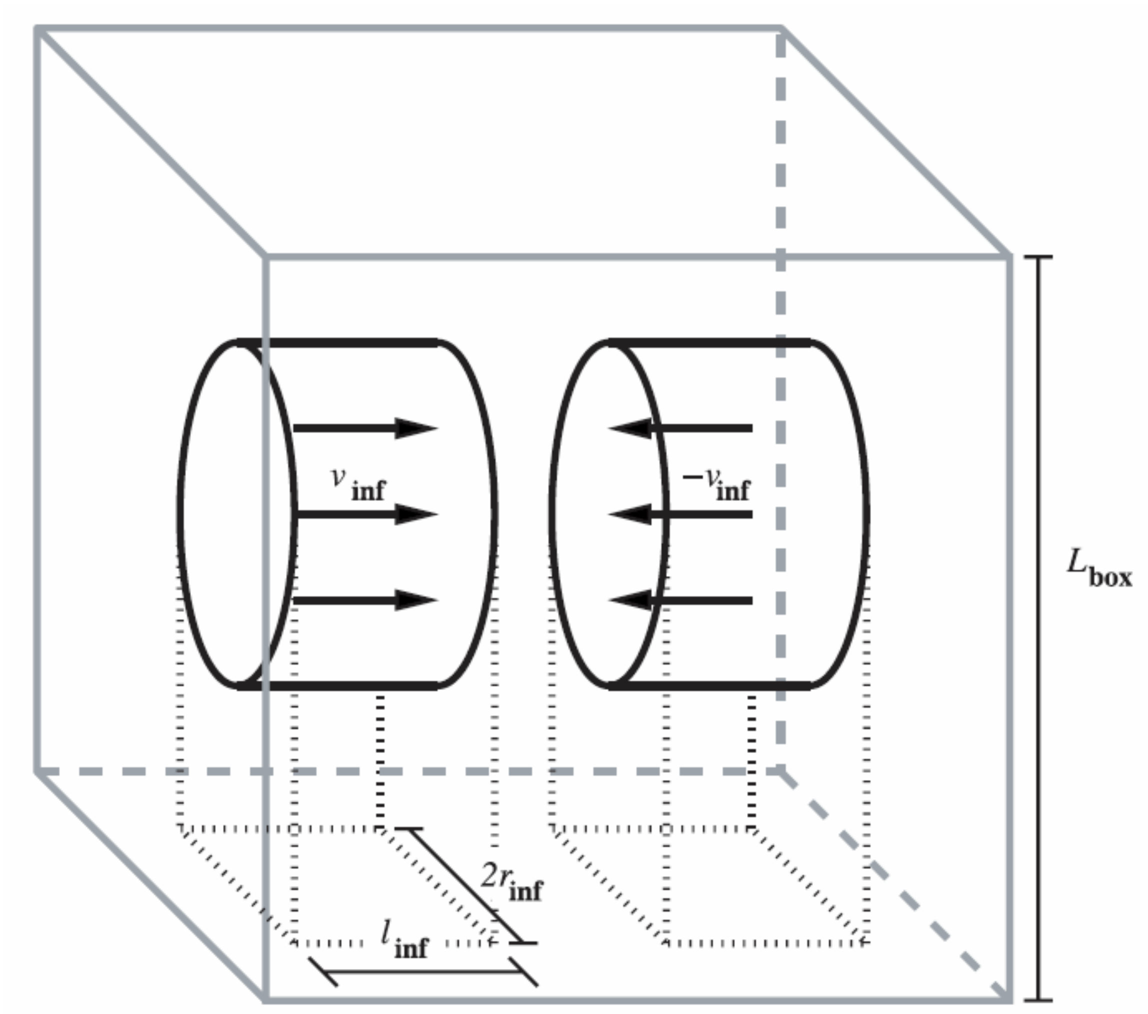
flattened collapsing structure
Mouschovias & Spitzer 1976

but: Ambipolar diffusion allows sub-critical cores to collapse

Formation of Molecular Clouds

3D simulations with FLASH*

Large scale converging flows



Vazquez-Semadeni et al. 2007

Fiducial model parameter:

- L_{box} = 256 pc, Δx_{min} = 0.03 pc
- l_{inf} = 112 pc
- r_{inf} = 32 pc
- v_{inf} = 6.9 km/sec = 1.22 M_a
- $n = 1\ cm^{-3}$
- $M_{inf} = 2.3 \times 10^4\ M_{sol}$
- T = 5000 K
- $M_J = 10^7\ M_{sol}$
- B = 1μG aligned with the flow
- μ = 3.3 (super-critical)

**Alliance Center for Astrophysical Thermonuclear Flashes (ASC), University of Chicago*

Current Version: 3.1

Numerical Method

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\mathbf{v}\, \rho) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla p_* = -\rho \mathbf{g}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\mathbf{v}\,(\rho E + p_*) - \mathbf{B}\,(\mathbf{v} \cdot \mathbf{B})) = \rho \mathbf{g} \cdot \mathbf{v} + \Gamma - \Lambda$$

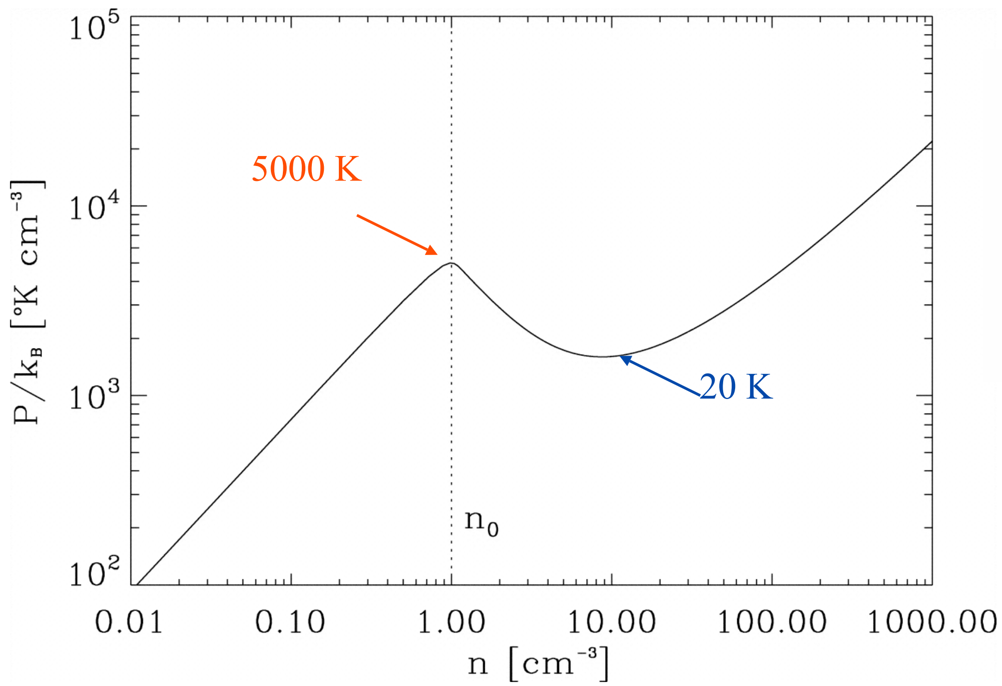
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0$$

$$E = \frac{1}{2} v^2 + \varepsilon + \frac{1}{2}\frac{B^2}{\rho},$$

$$p_* = p + \frac{B^2}{2},$$

$$p = (\gamma - 1)\, \rho \epsilon$$

$$\mathbf{g} = -\nabla \Phi \qquad \Delta \Phi = 4\pi G \rho$$



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Koyama & Inutsuka '02

Ideal MHD + self-gravity + ideal gas + heating & cooling

Formation of Molecular Clouds

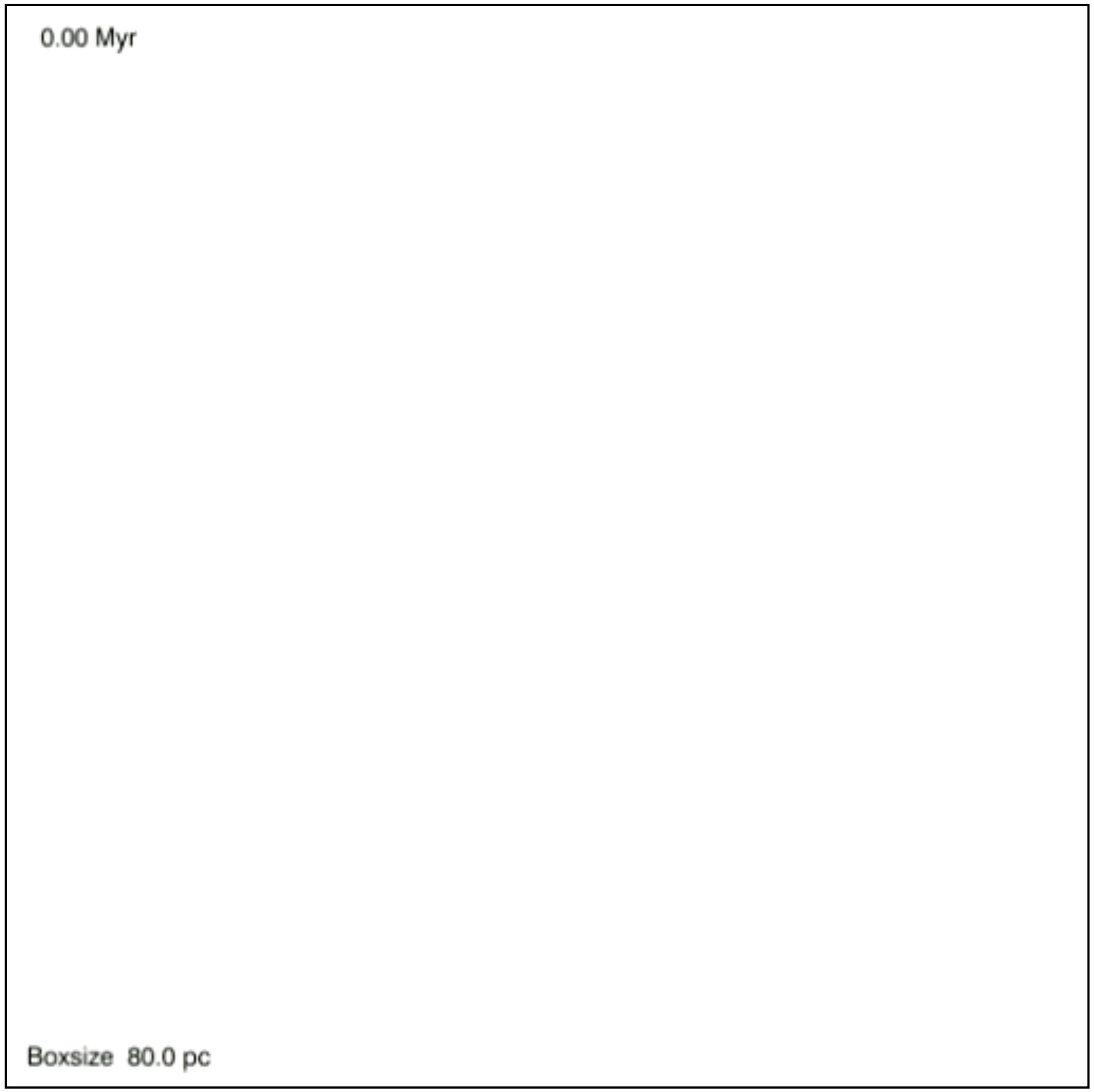
the non-magnetic case

edge-on view

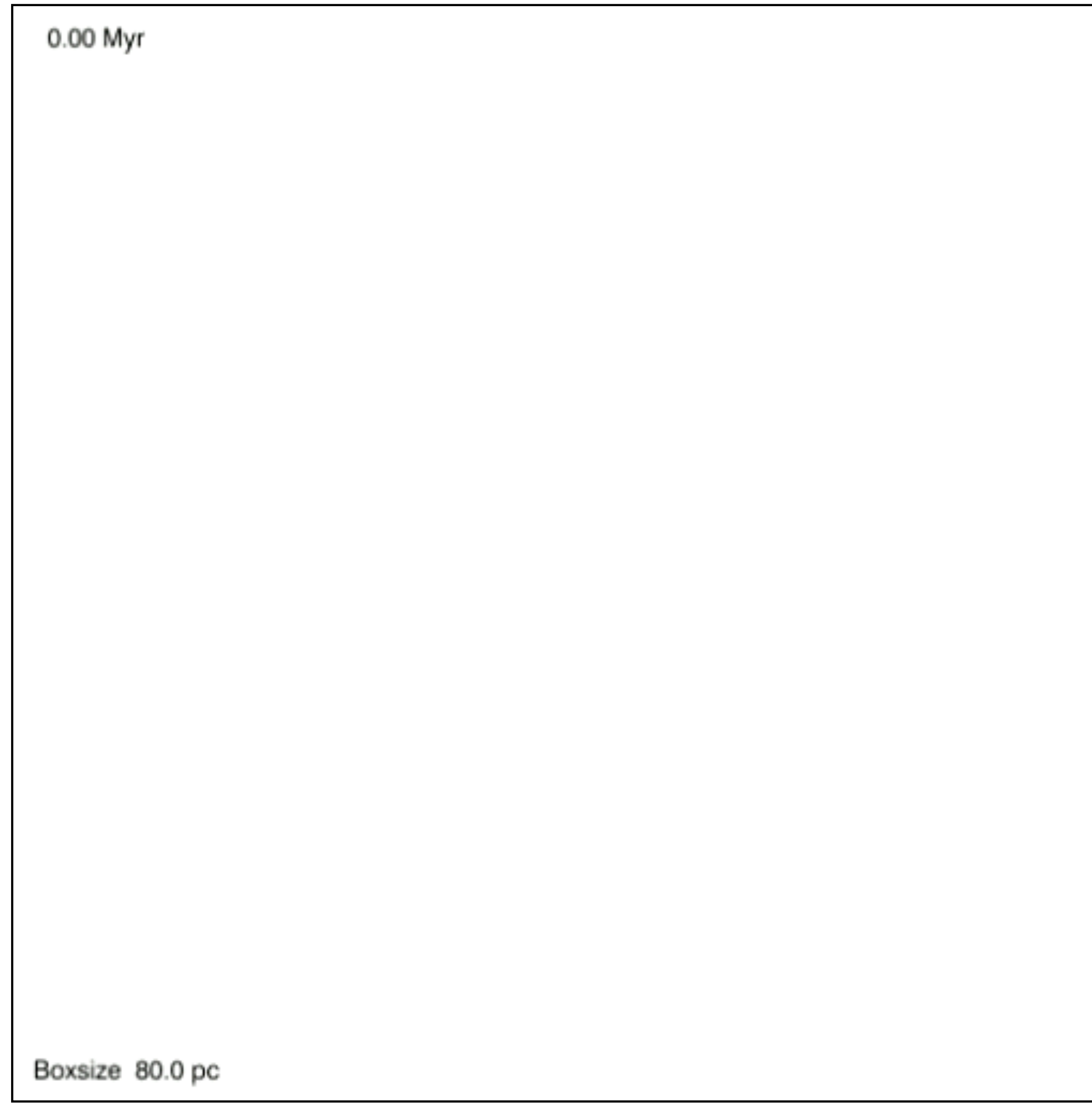
face-on view

Formation of Molecular Clouds

the non-magnetic case



edge-on view

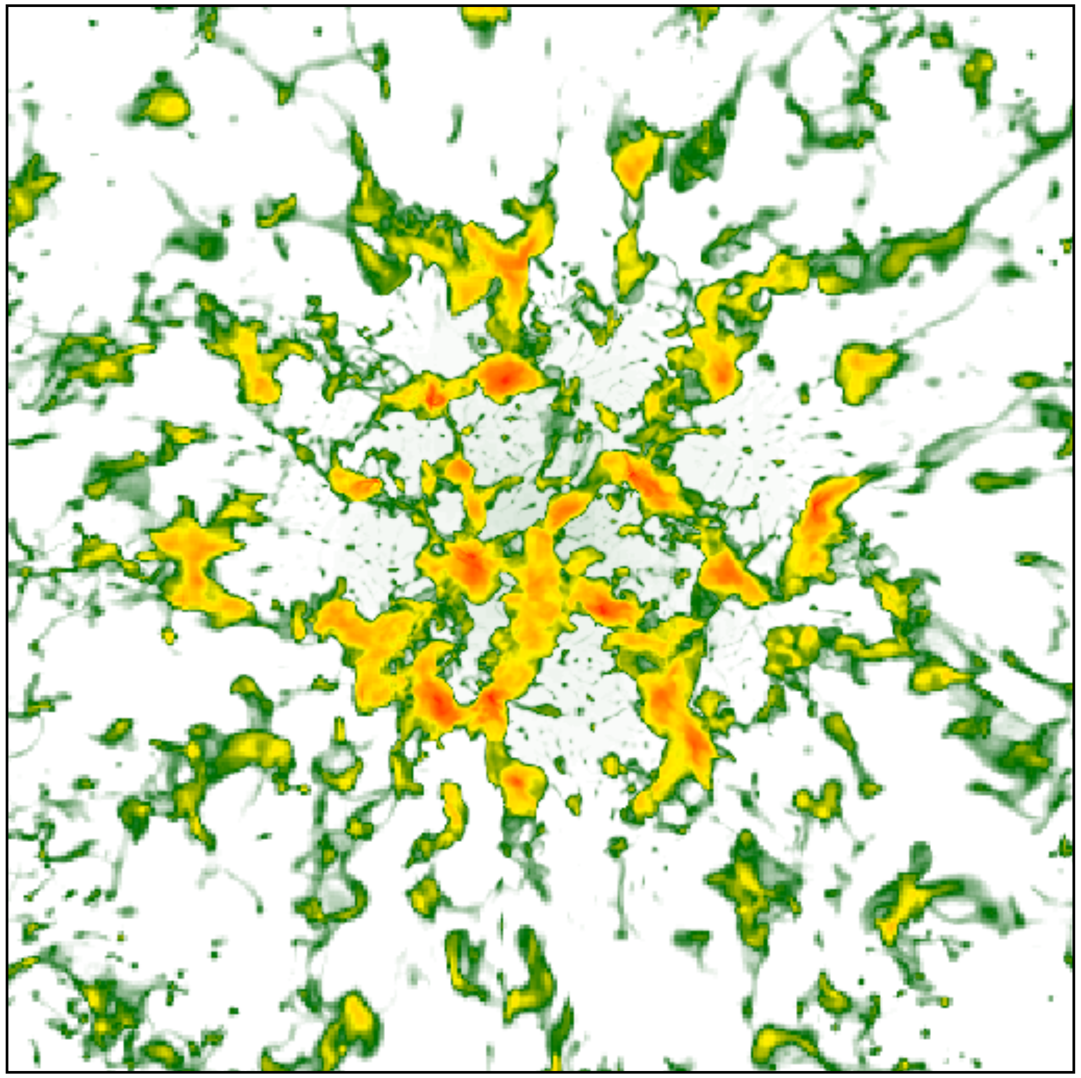


face-on view

Formation of Molecular Clouds

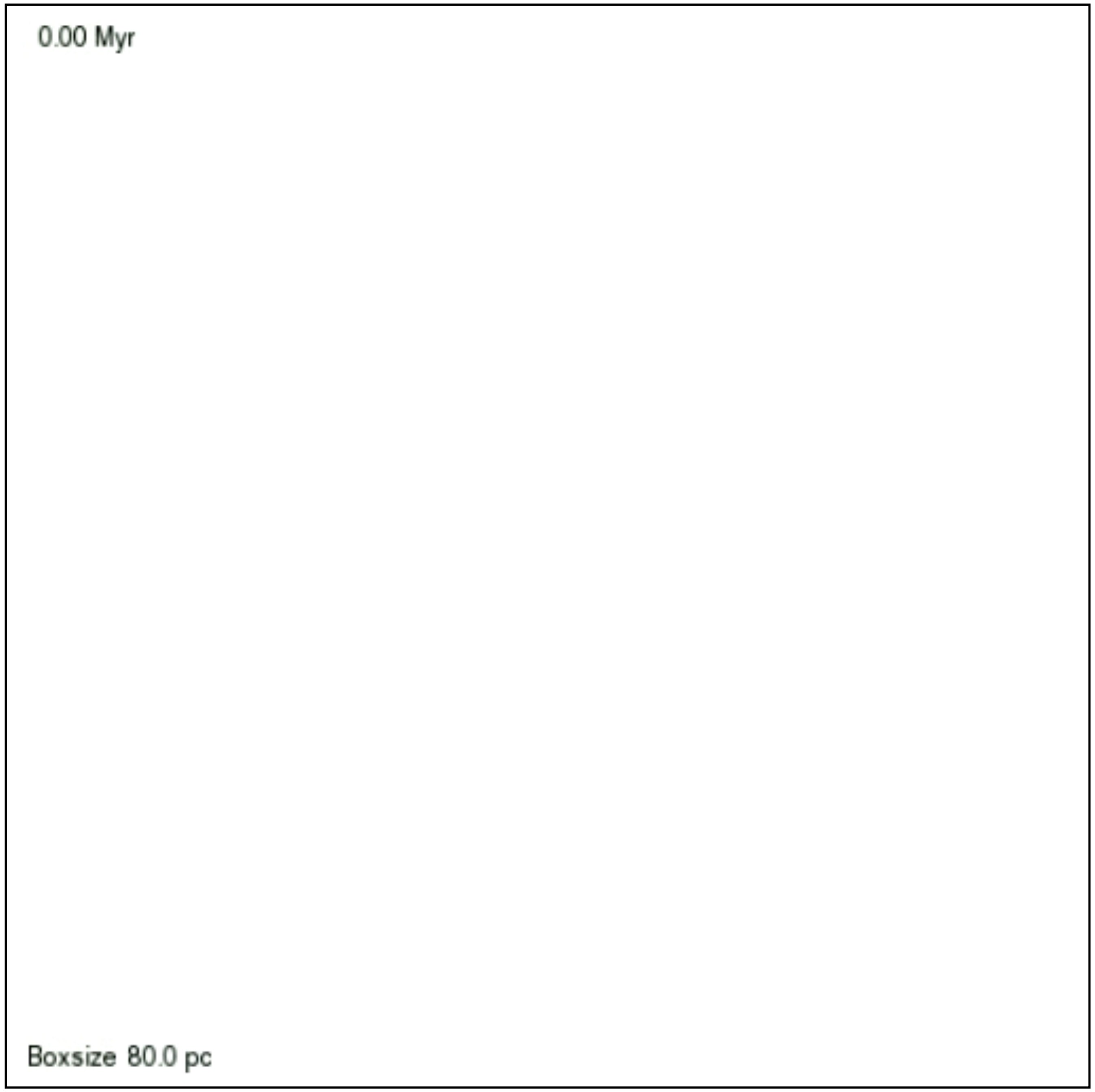
main properties of MCs:

- highly patchy and clumpy
- high fraction of substructure
- cold dense molecular clumps coexist with warm atomic gas
- not a well bounded entity
- dynamical evolution (different star formation modes: from low mass to high mass SF?)

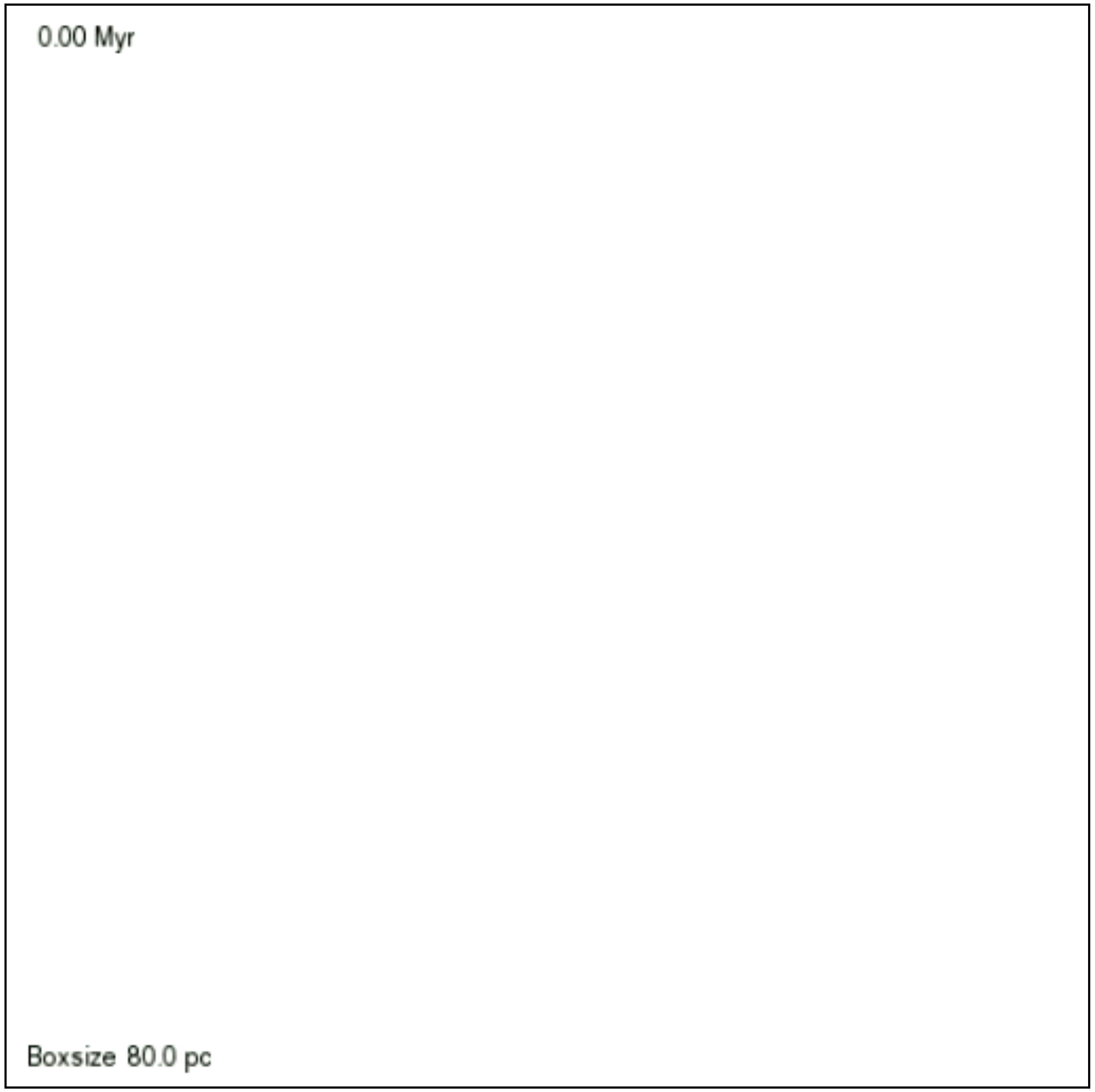


Formation of Molecular Clouds

the weakly magnetized ($B_x = 1\mu G$) case



edge-on view



face-on view

Formation of Molecular Clouds

with random component: $B_x = 3\mu G + \delta b = 3\mu G$

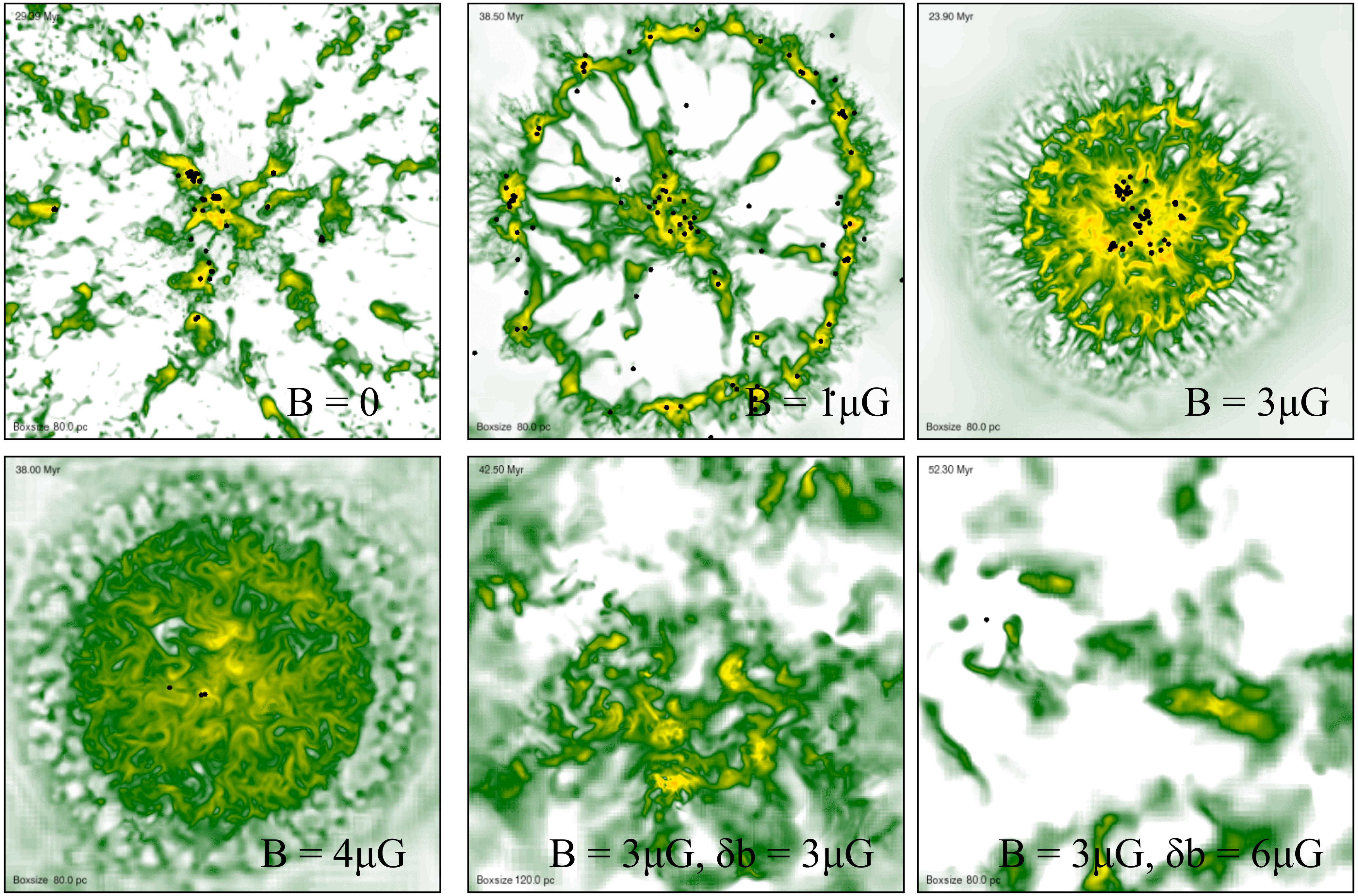
face-on view

Formation of Molecular Clouds

with random component: $B_x = 3\mu G + \delta b = 3\mu G$

face-on view

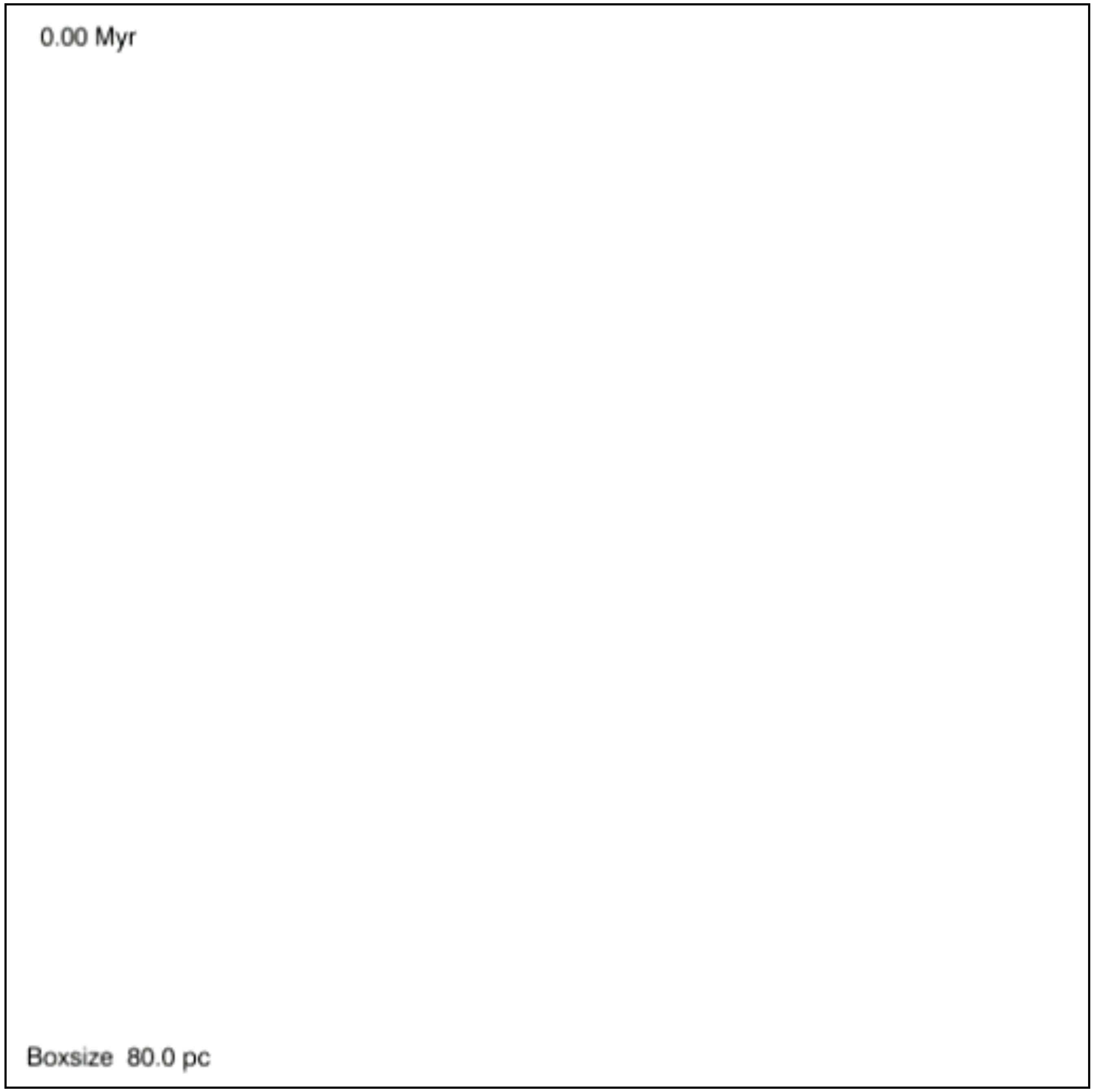
Formation of Molecular Clouds



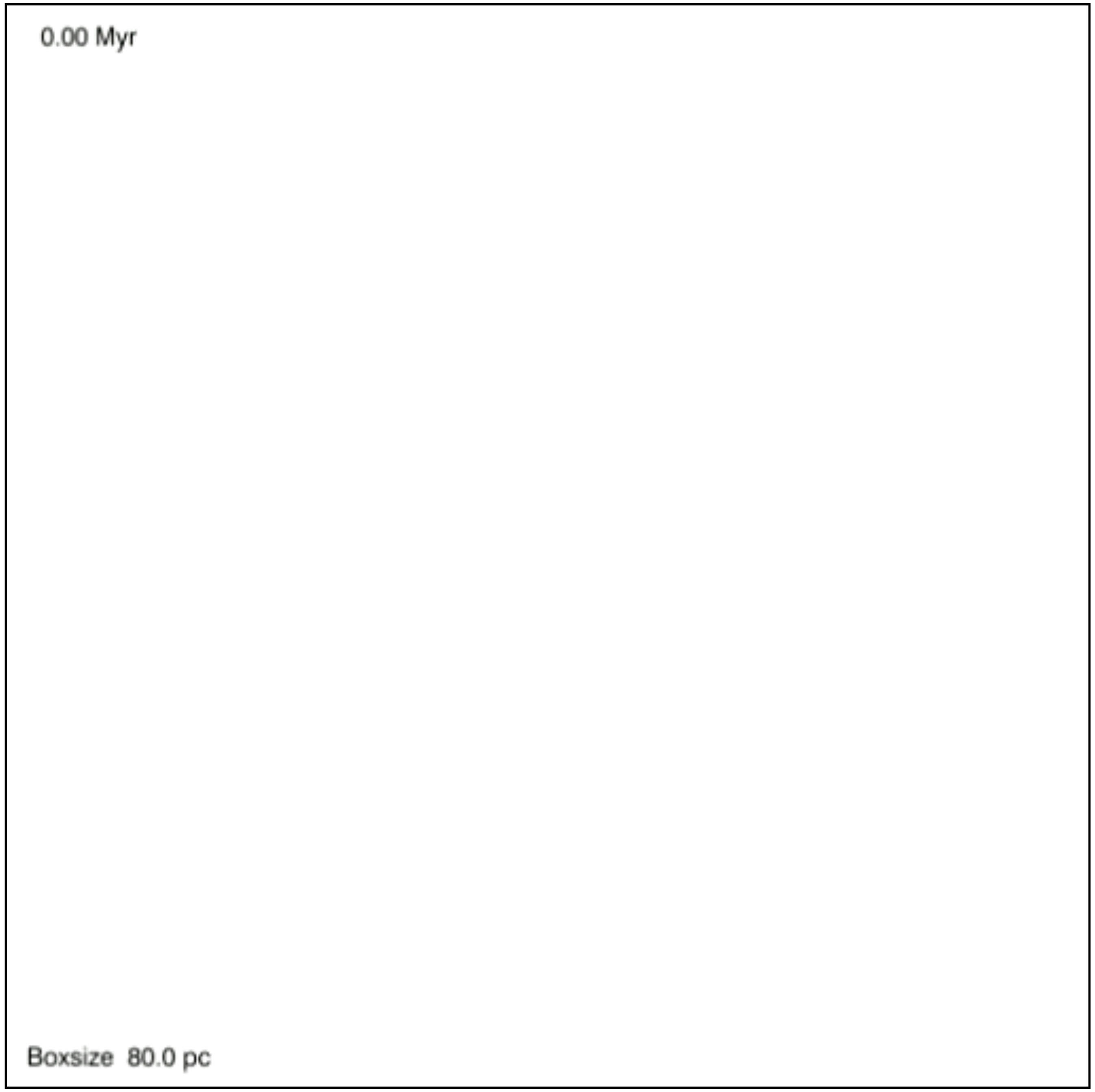
Morphology of the molecular cloud and star formation efficiency depends on the strength of the magnetic field

Formation of Molecular Clouds

Influence of Ambipolar Diffusion: $B_x = 3\mu G$ (super-critical)



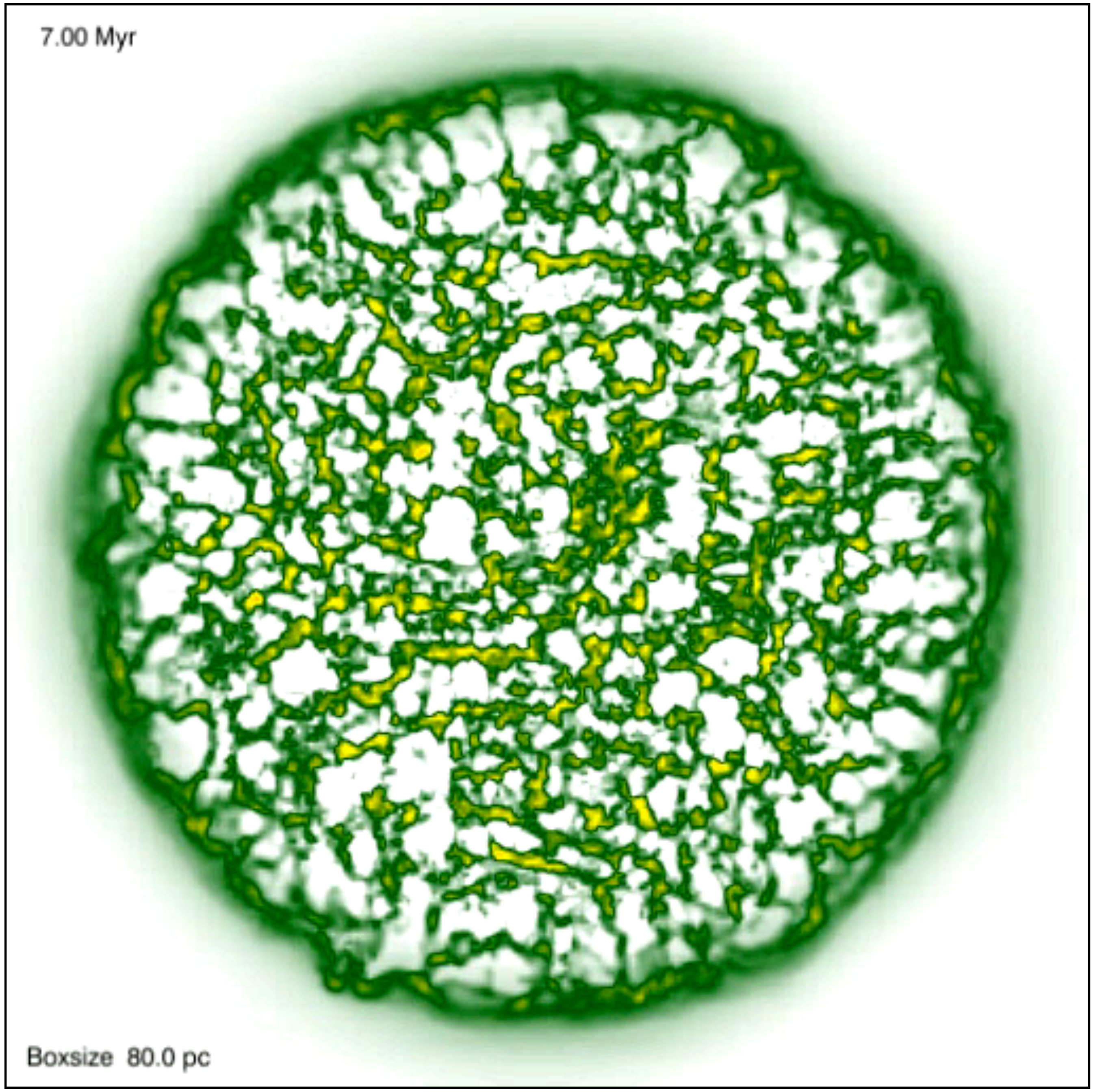
Ideal MHD



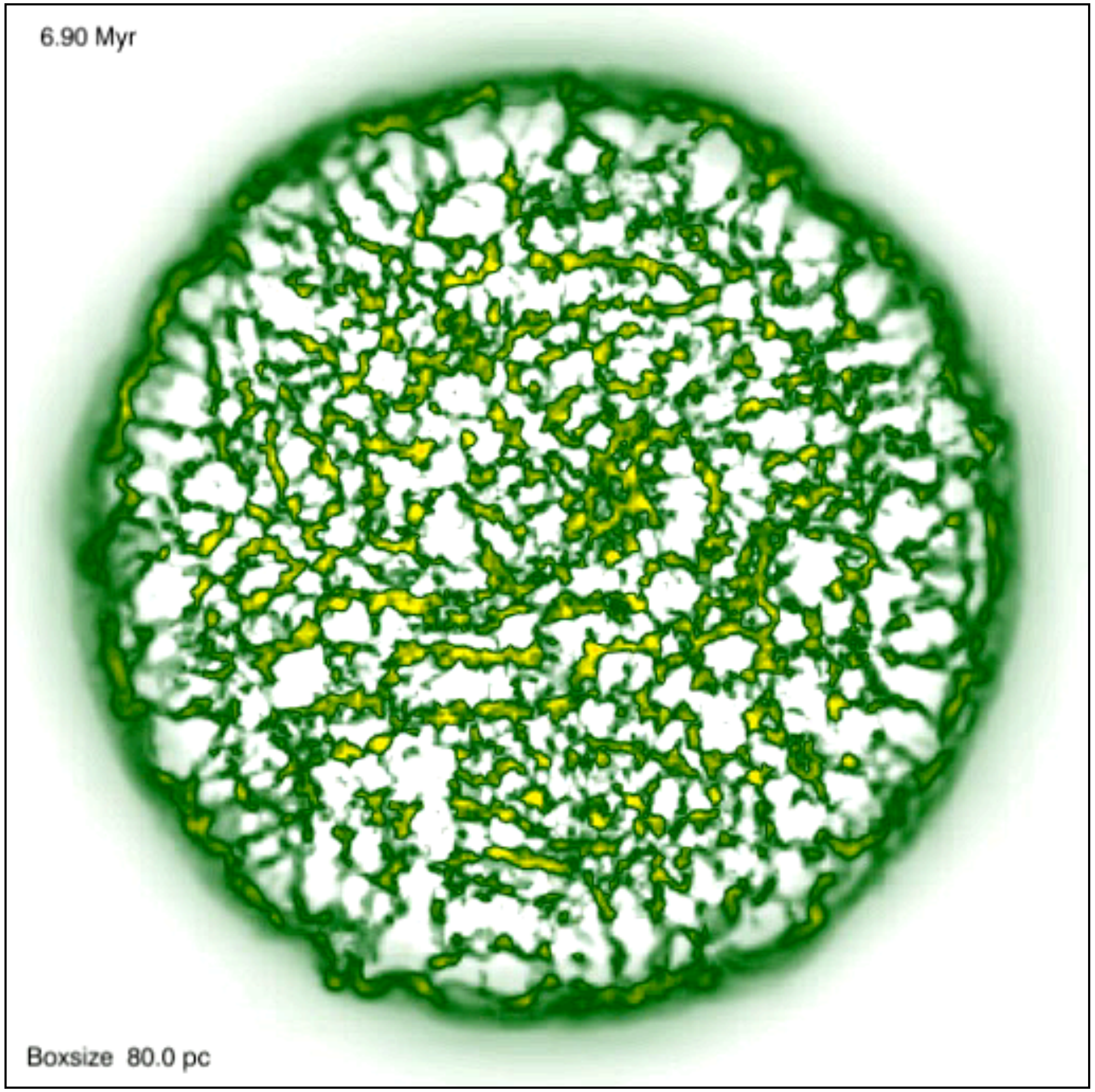
with AD

Formation of Molecular Clouds

Influence of Ambipolar Diffusion: $B_x = 4\mu G$ (critical)



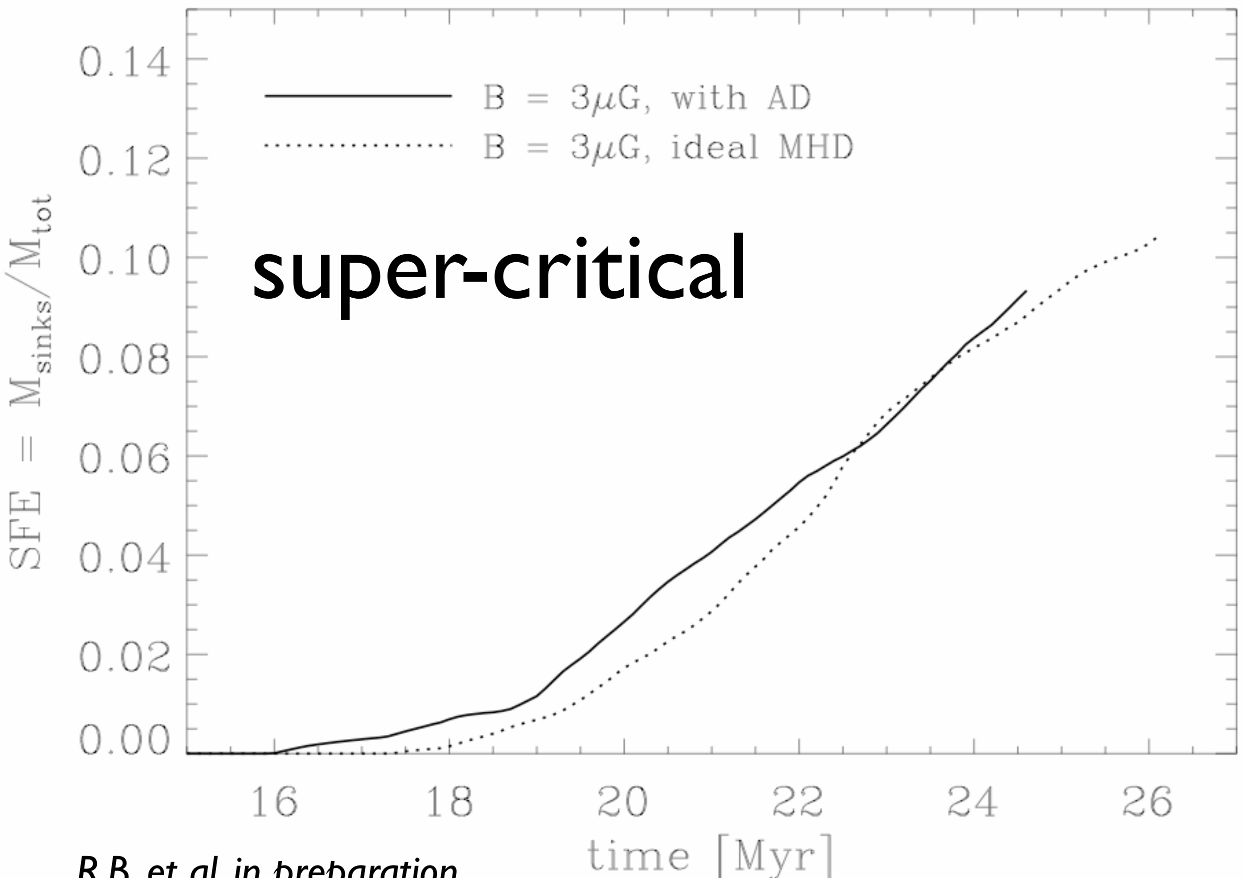
Ideal MHD

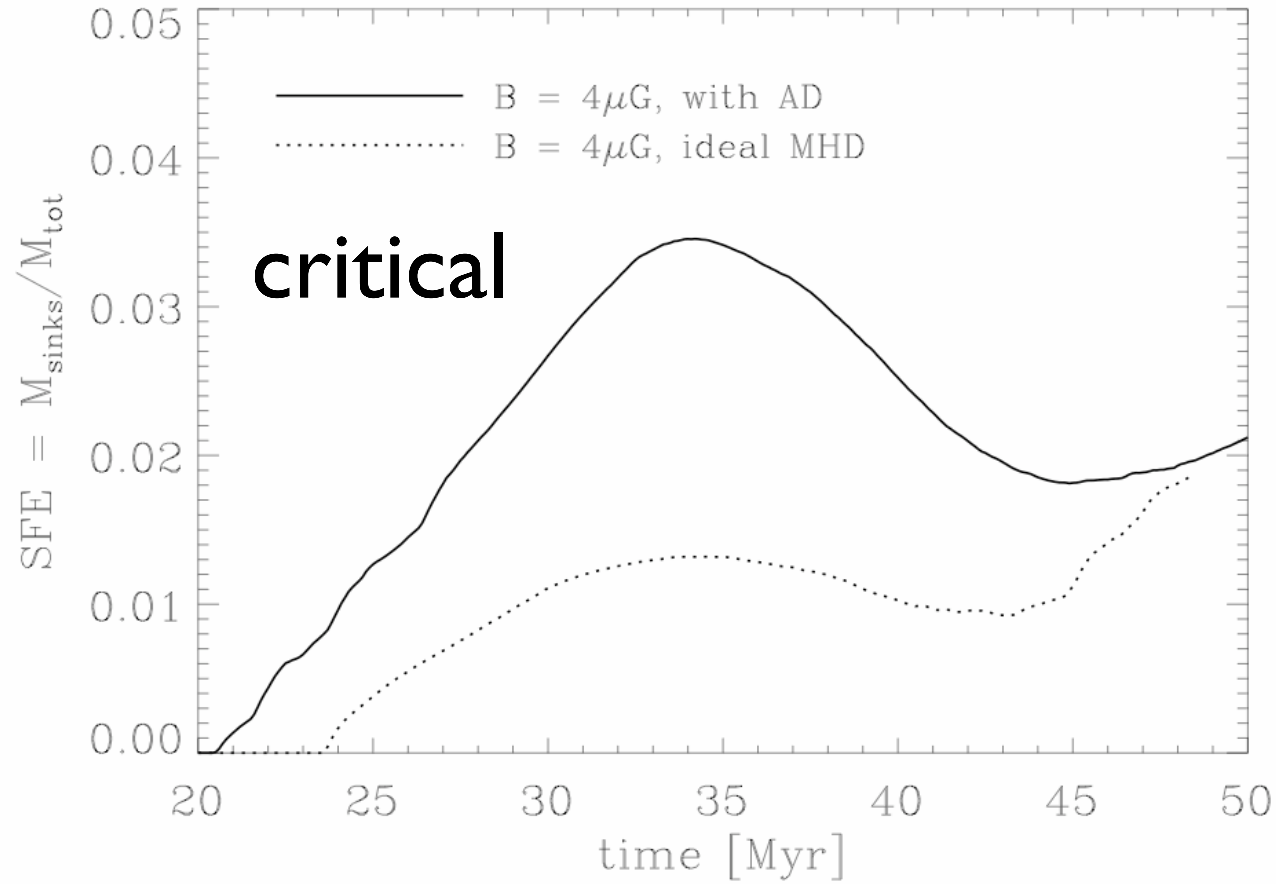


with AD

Formation of Molecular Clouds

Influence of Ambipolar Diffusion

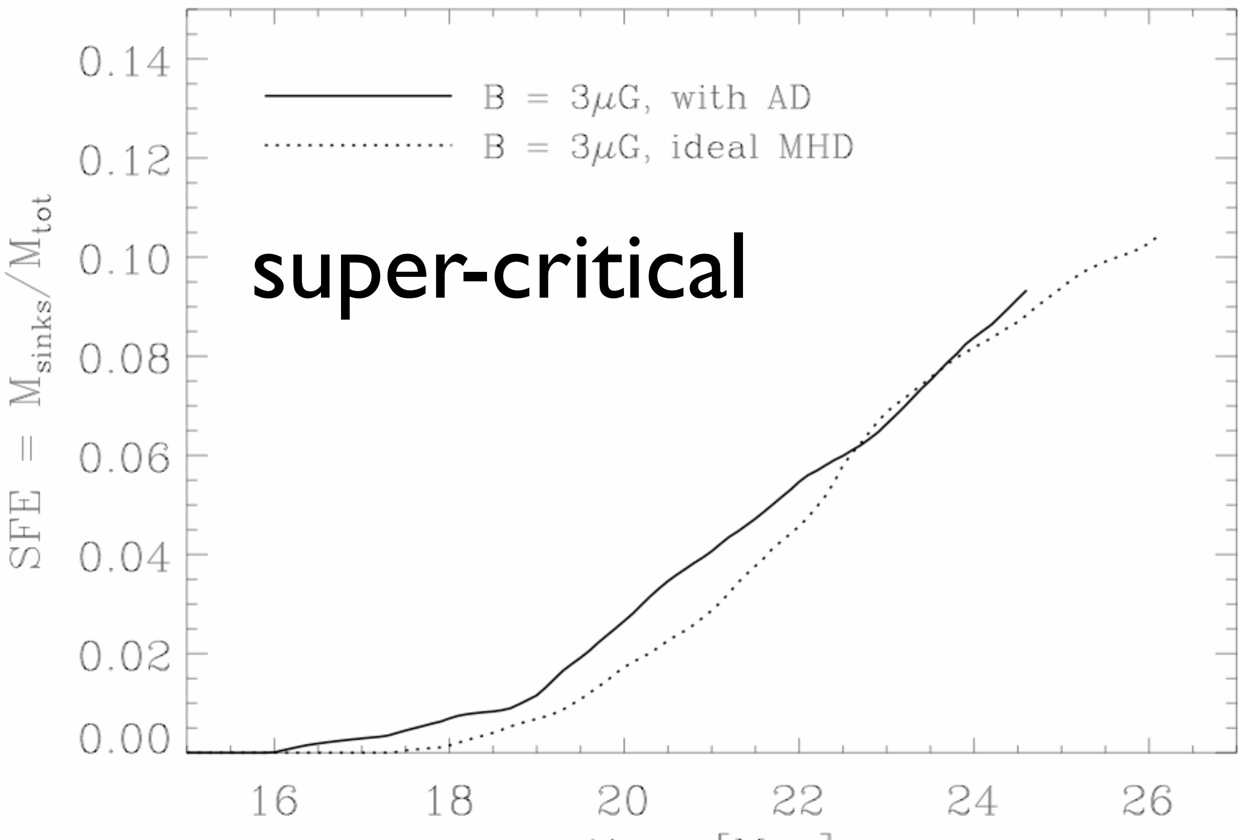


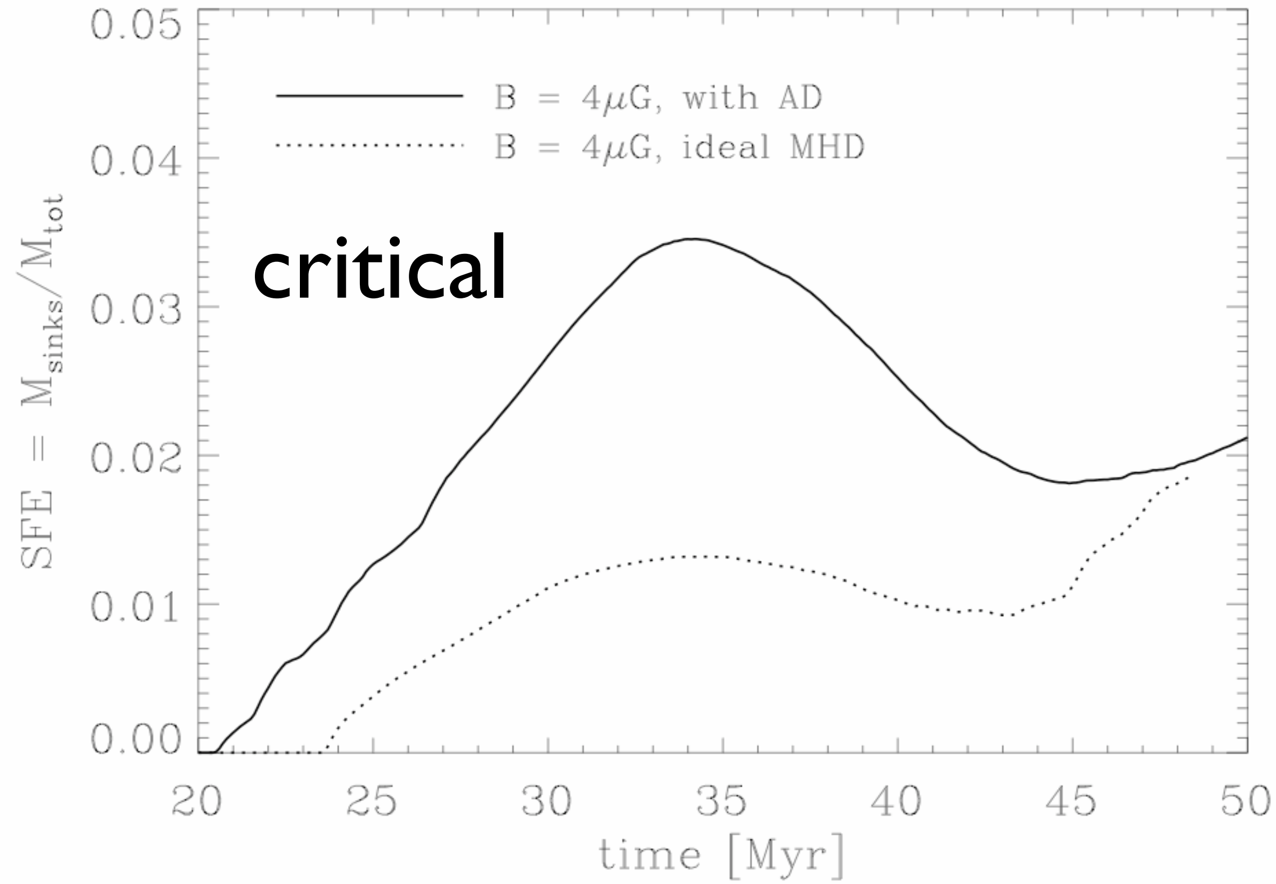


R.B. et al. in preparation

Formation of Molecular Clouds

Influence of Ambipolar Diffusion



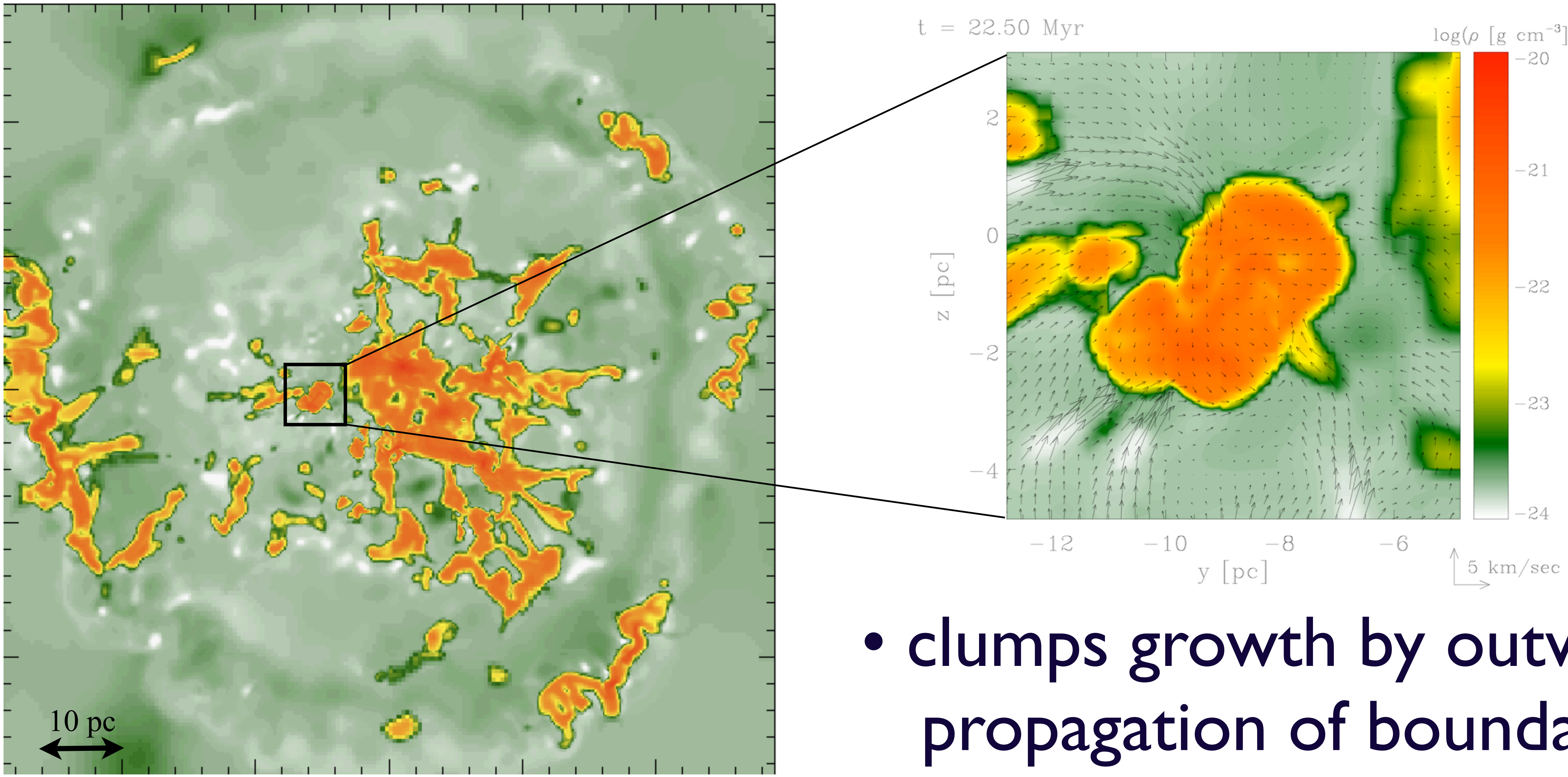


R.B. et al. in preparation

- Ambipolar diffusion is **not** a major player for star formation

Formation of Molecular Clouds

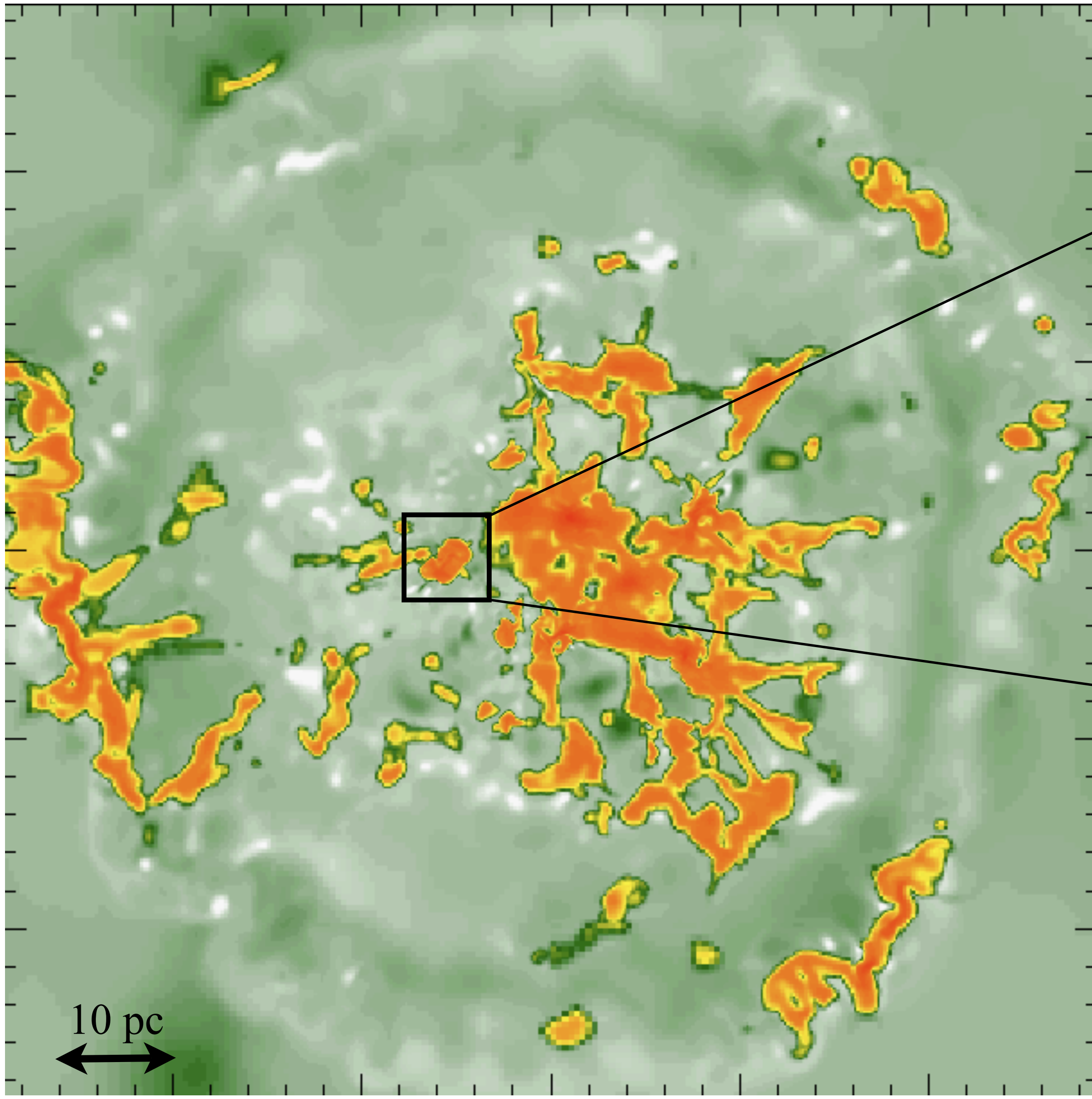
morphology and clump evolution

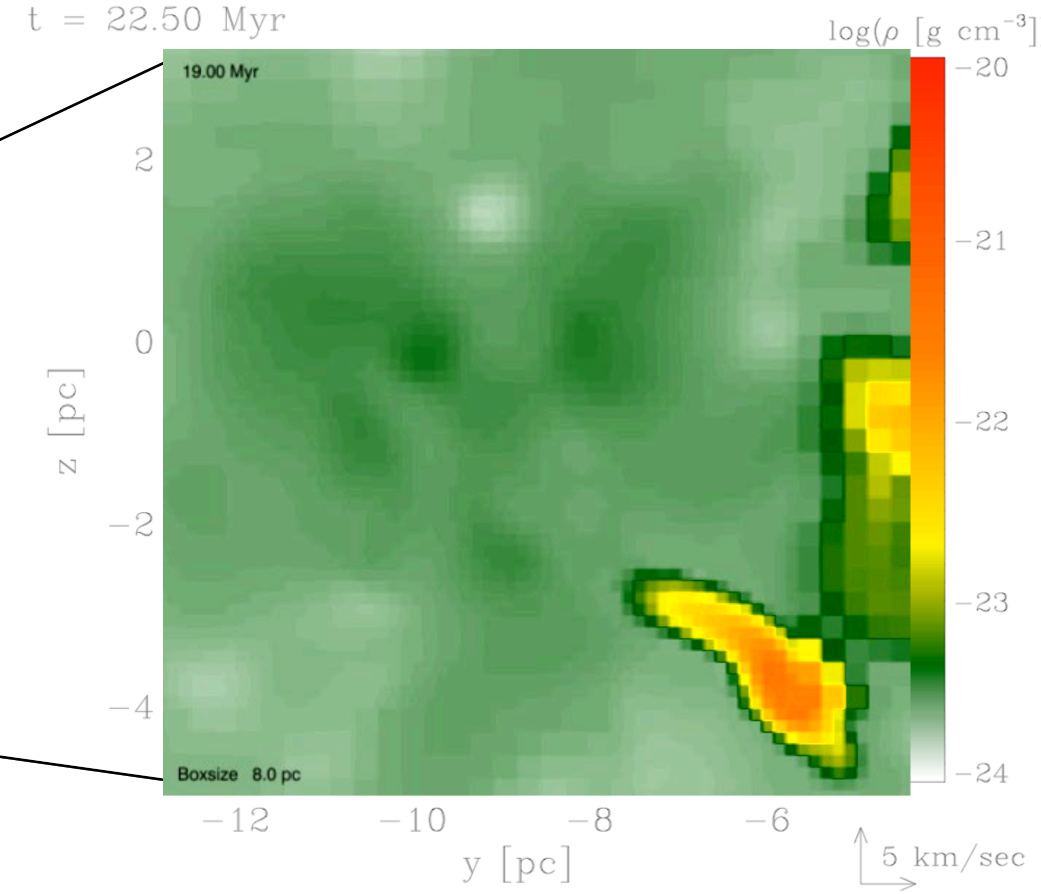


- MCs are inhomogeneous
- cold clumps embedded in warm atomic gas
- clumps growth by outward propagation of boundary layers and
- coalescence at later times

Formation of Molecular Clouds

morphology and clump evolution



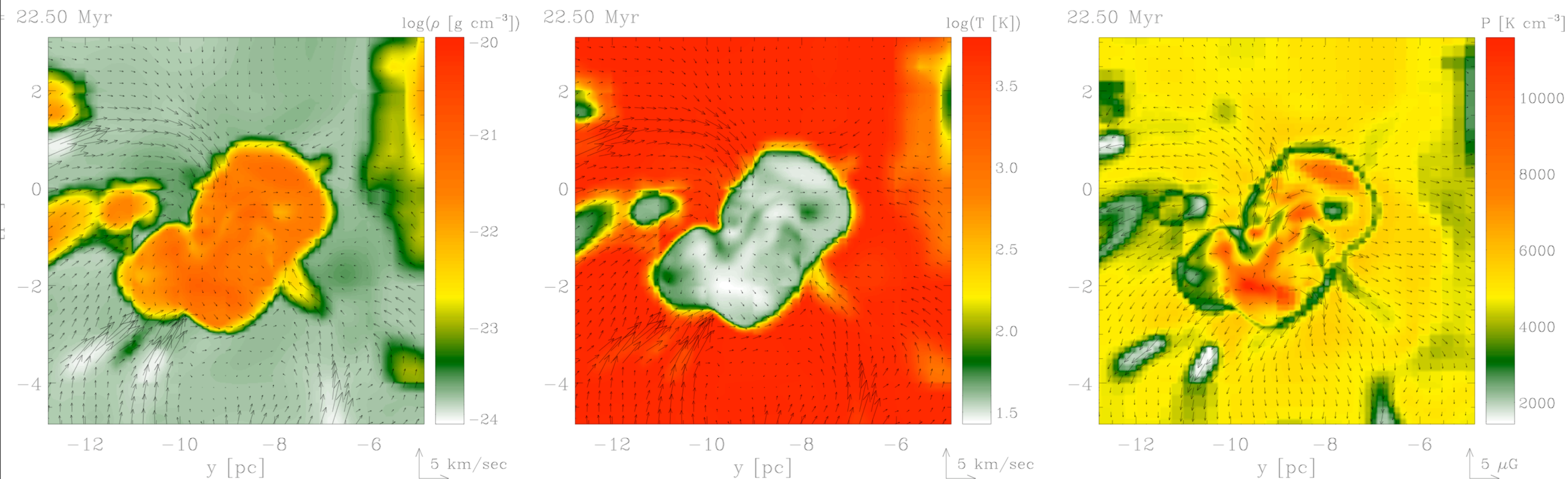


- MCs are inhomogeneous
- cold clumps embedded in warm atomic gas

- clumps growth by outward propagation of boundary layers and
- coalescence at later times

Formation of Molecular Clouds

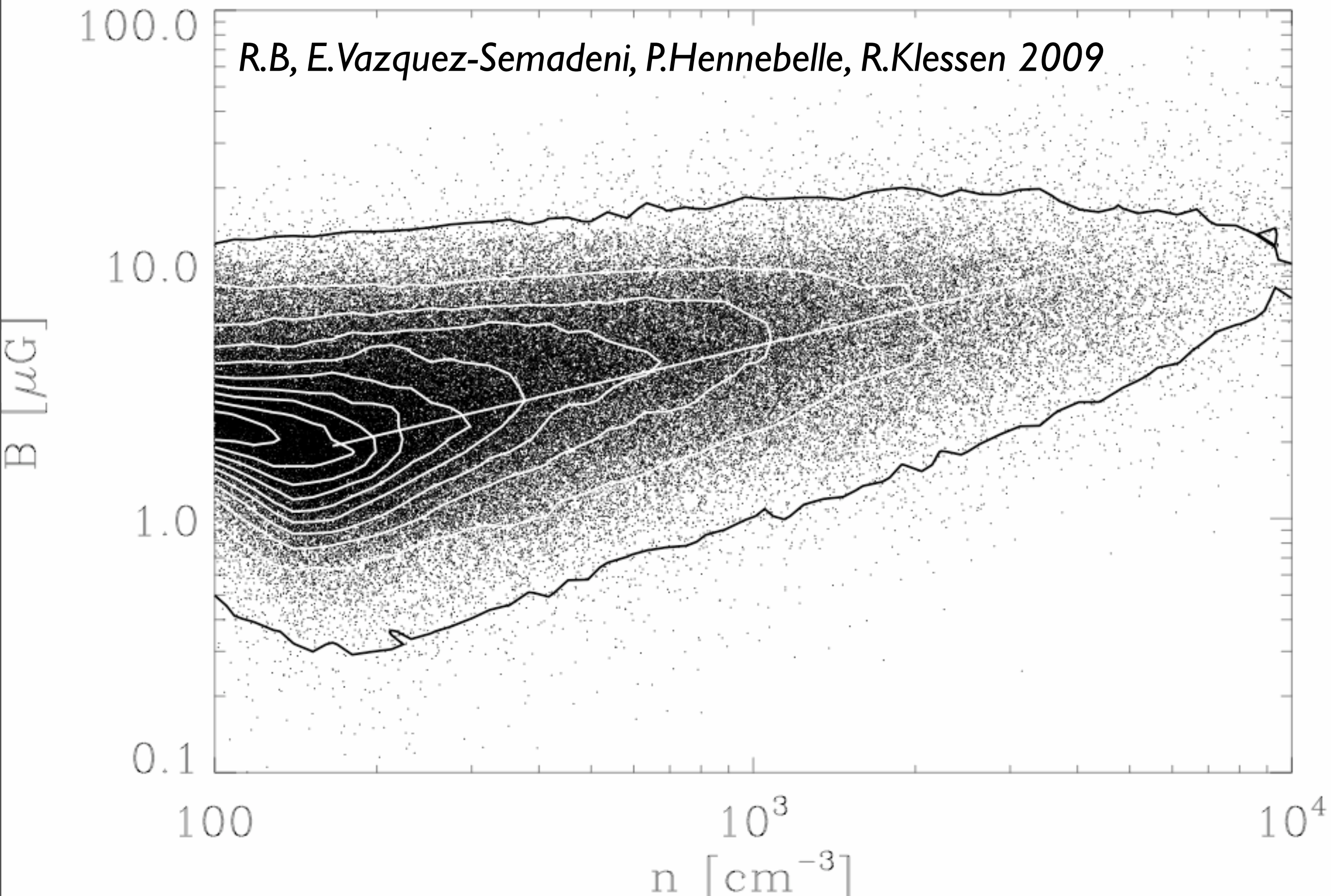
clump morphology



R.B, E.Vazquez-Semadeni, P.Hennebelle, R.Klessen 2009

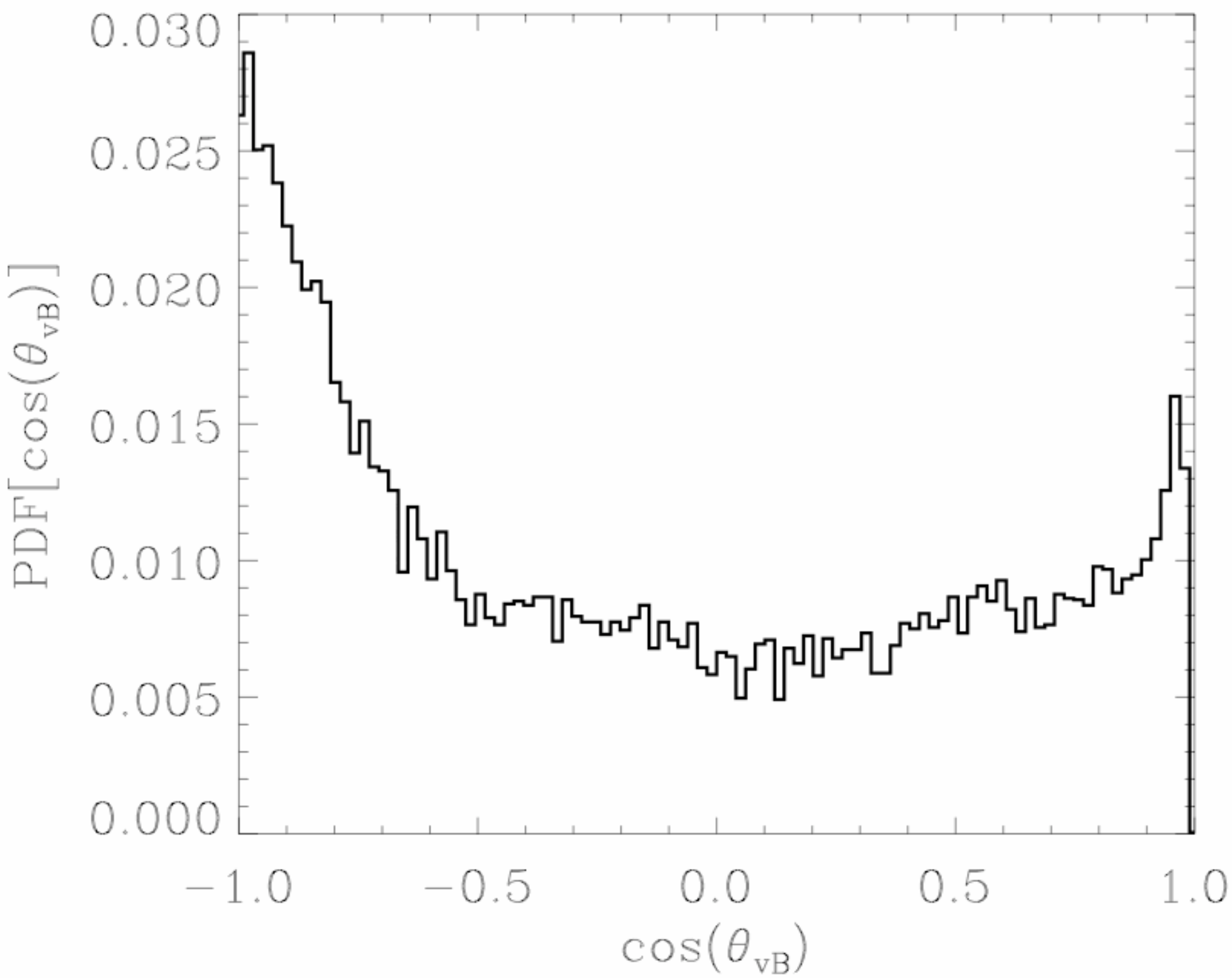
- cold clumps are in near pressure equilibrium (ram+thermal) with their warm surroundings
- in-falling gas streams along field lines

Formation of Molecular Clouds



- **large** scatter of magnetic field strengths: sub- and super-critical cores exist
- median slope: $B \propto n^{0.5}$ (e.g. *Crutcher 1999*)

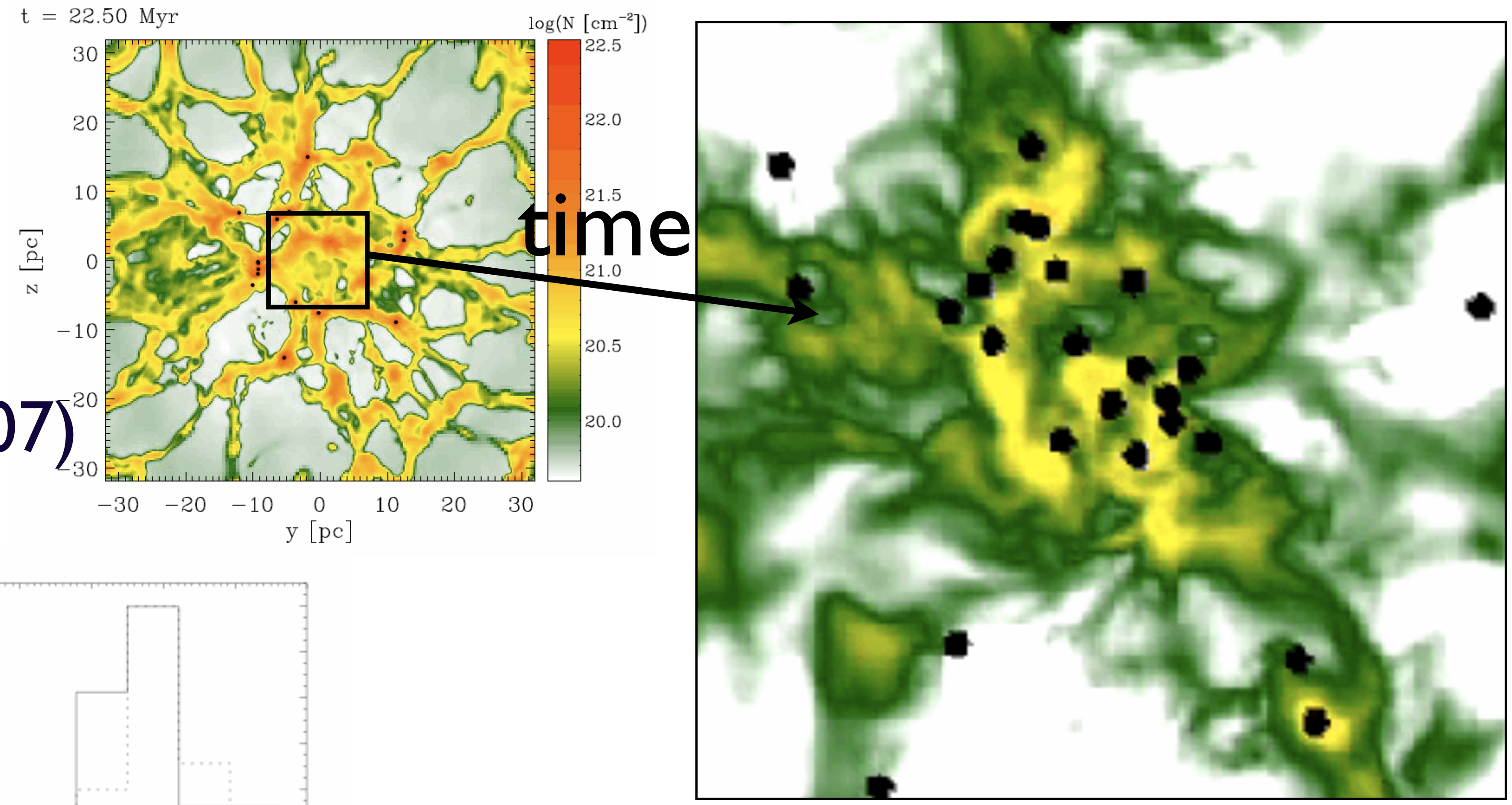
- **strong** correlation of gas streams and magnetic field lines

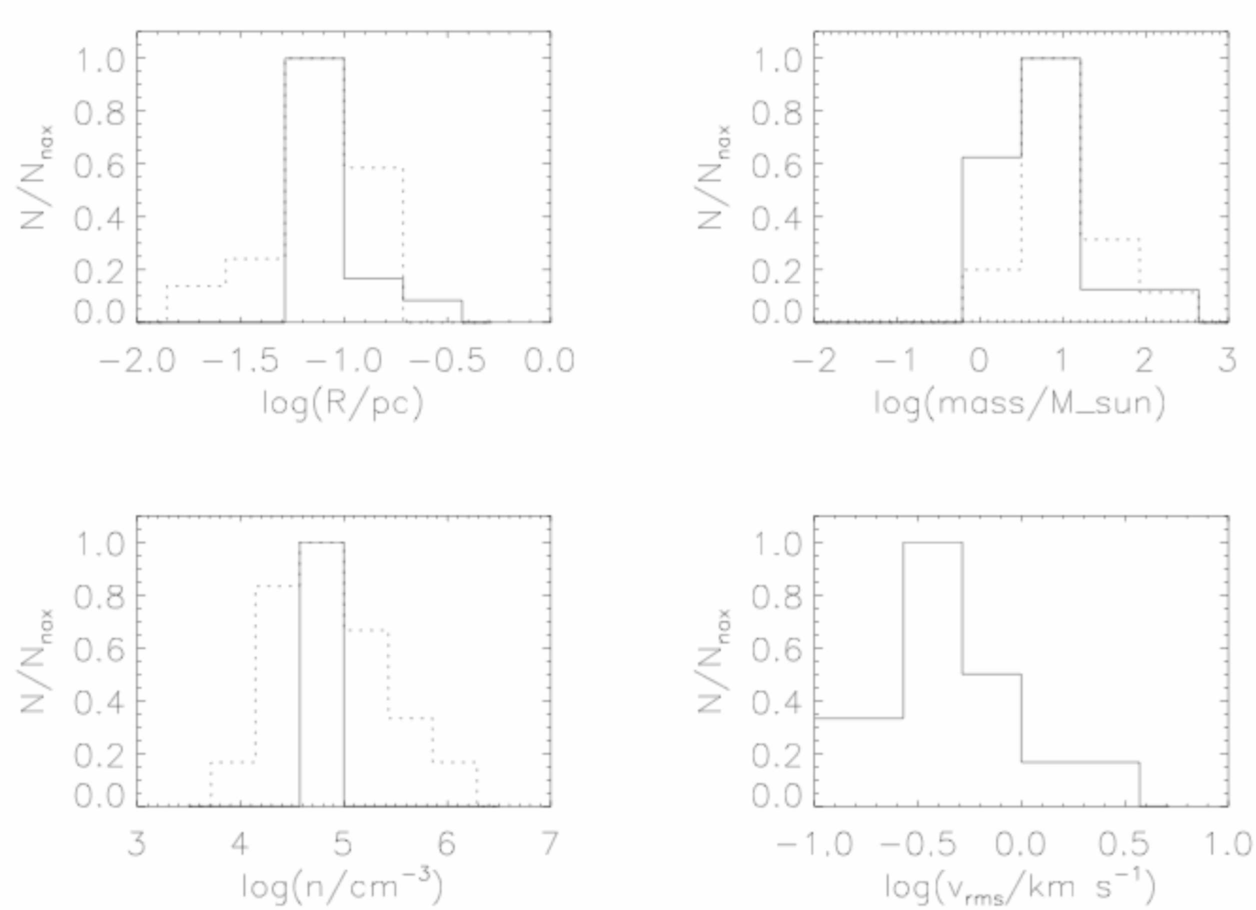


Formation of Molecular Clouds

global contraction phase

centre of the cloud
→ birthplace for
massive stars?
(eg. Zinnecker & Yorke 2007)

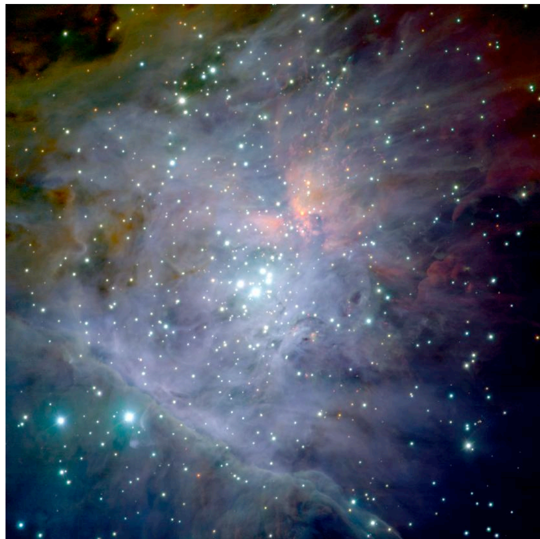




Vazquez-Semadeni et al. 2008

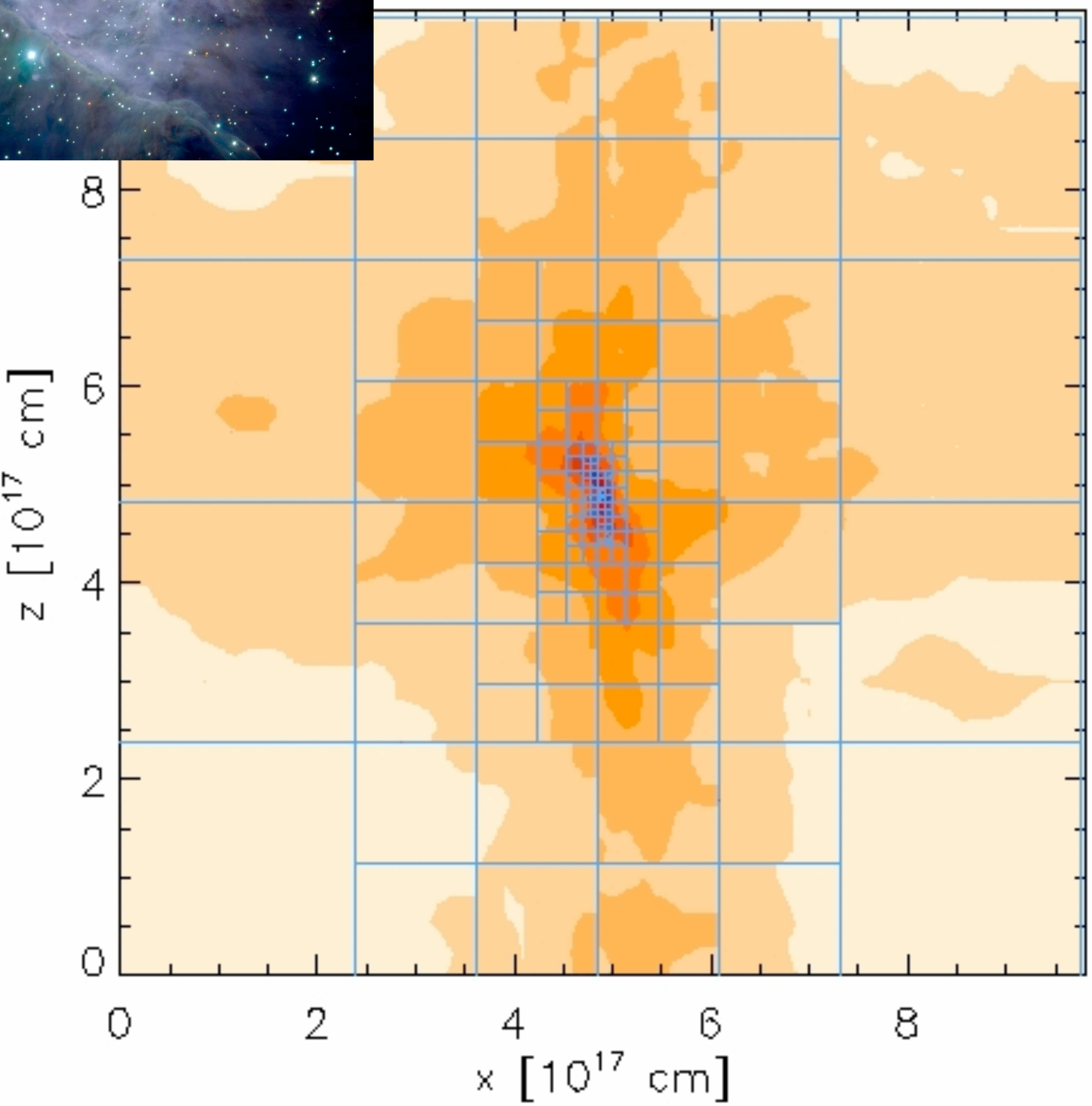
comparison of core properties with observation of Cygnus X by *Motte et al 2007*

Collapse of turbulent cores



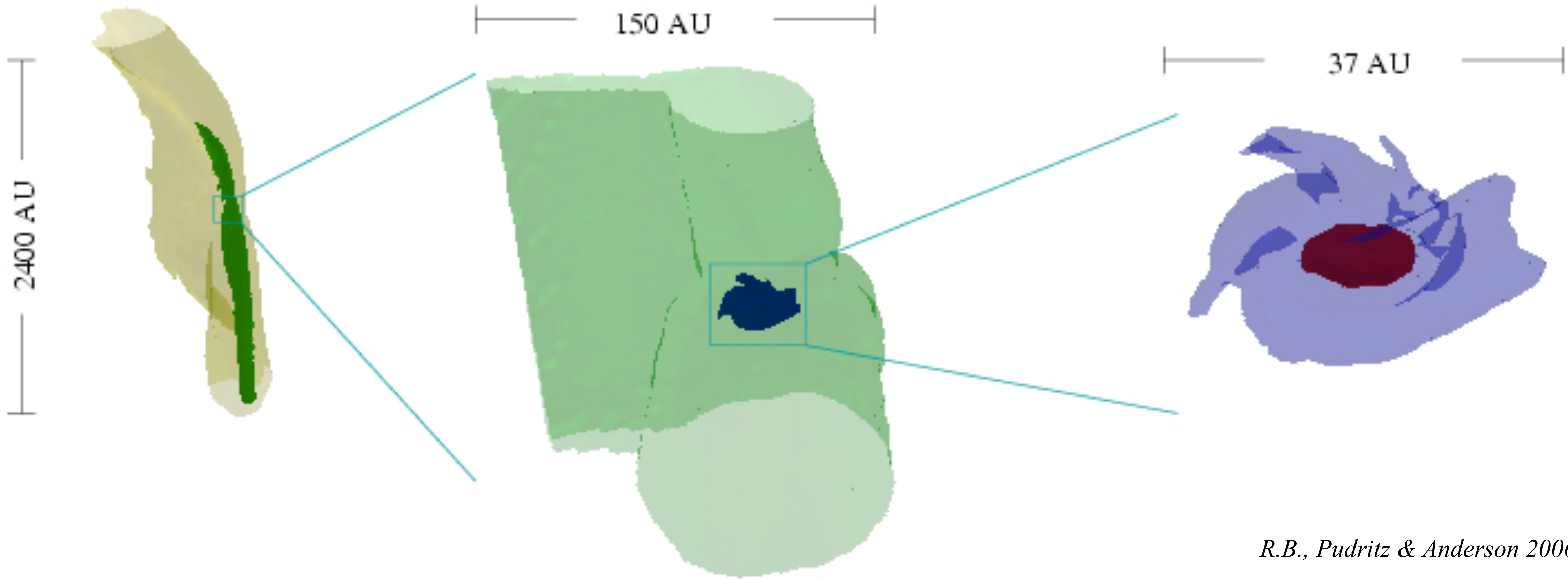
SF out of **turbulent** molecular clouds

(e.g. *Mac Low & Klessen 2004*)



- Initial data from *Tilley & Pudritz 2004*: ZEUS simulations of core formation within a supersonic **turbulent** environment
- $L = 0.32$ pc, $M_{tot} = 105\ M_{sol}$
- Follow the collapse of the densest most **massive** region: $\sim 23\ M_{sol}$
- Final resolution: $\sim R_{sol}$ (27 refinement levels)

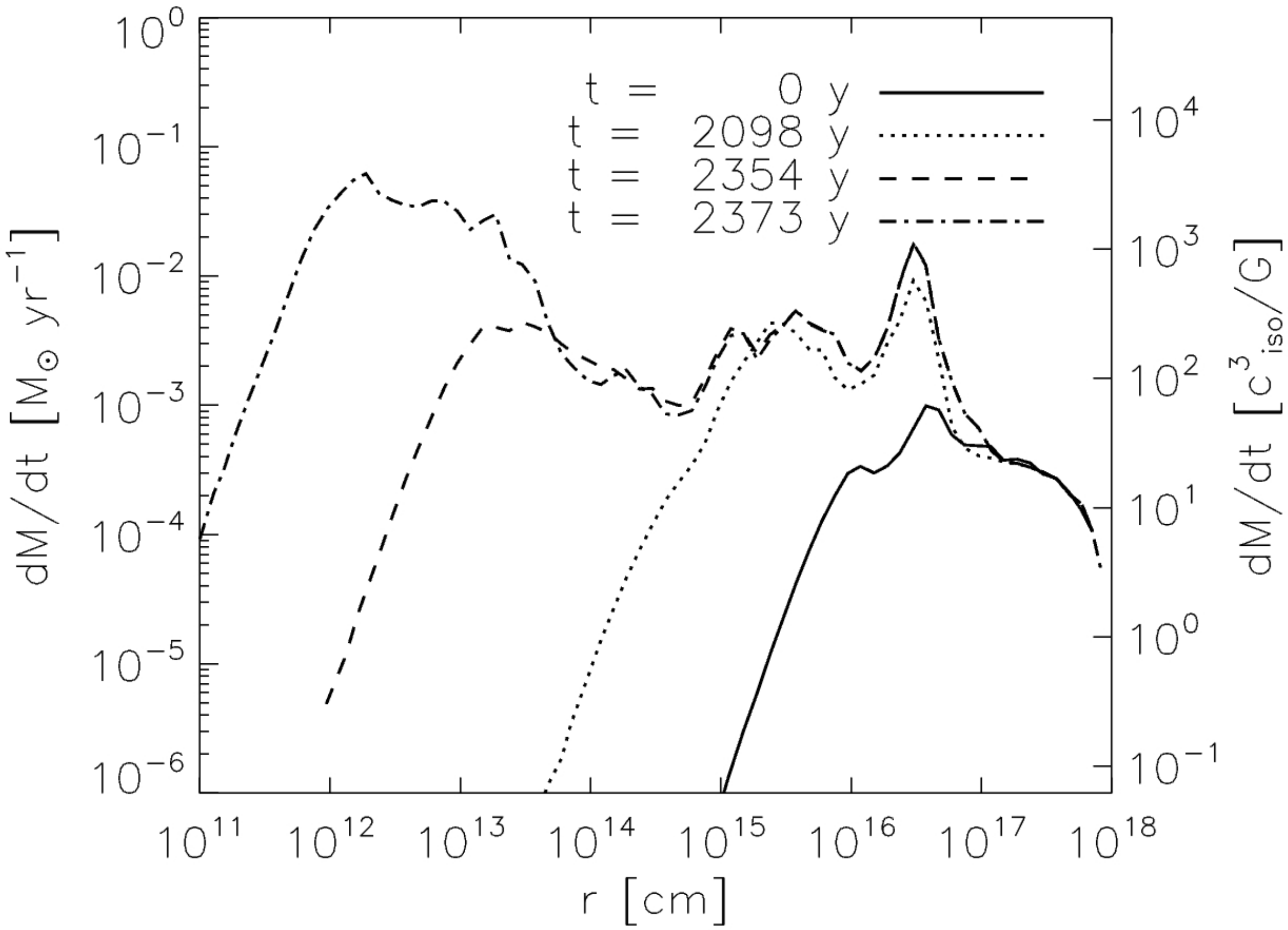
Collapse of turbulent cores

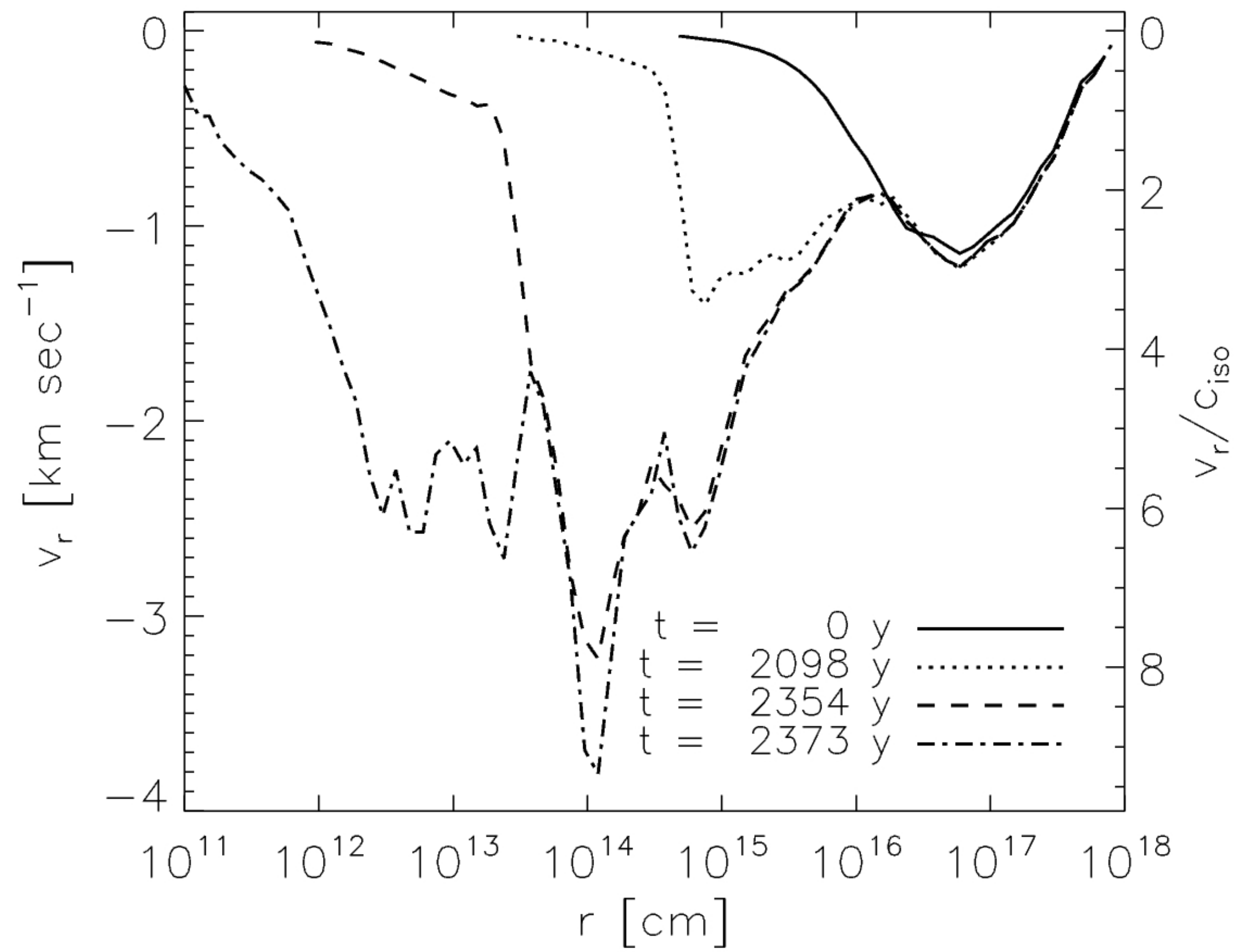


R.B., Pudritz & Anderson 2006

- **Filament** with an attached sheet
- small **disk** within the filament (perpendicular)
- adiabatic (optically thick) core
- very efficient gas **accretion** through the filament

Formation of massive stars

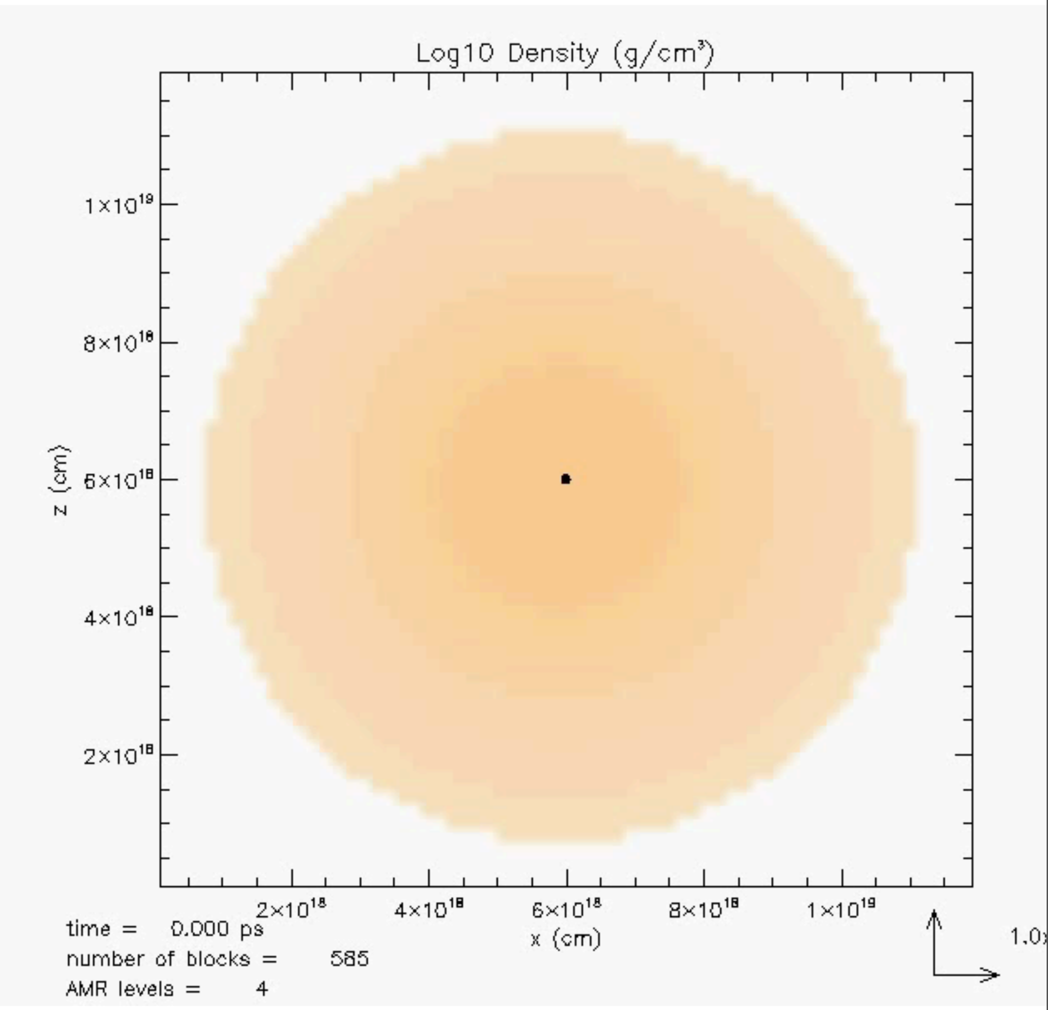




- Very **high** accretion rates through dense filaments: up to 10^{-3} - 10^{-2} M_{sol}/year
- Mass accretion rates are higher than limits from radiation pressure of **massive** stars (e.g. *Wolfire & Cassinelli 1987*: 10^{-3} M_{sol}/year)

Massive Star Formation: Dynamics of HII Regions

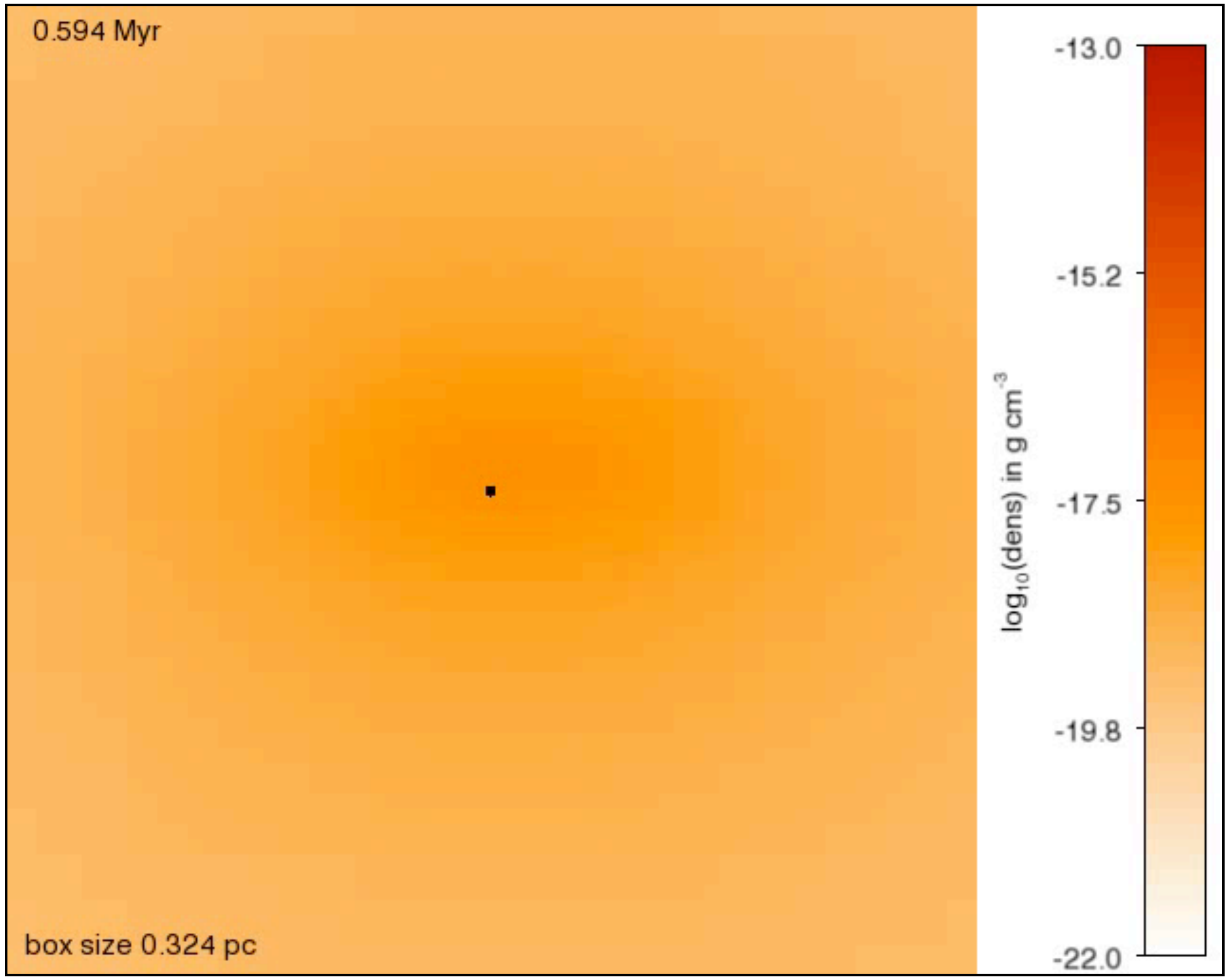
3D Simulations of collapsing cloud cores with ionization feedback from young massive stars



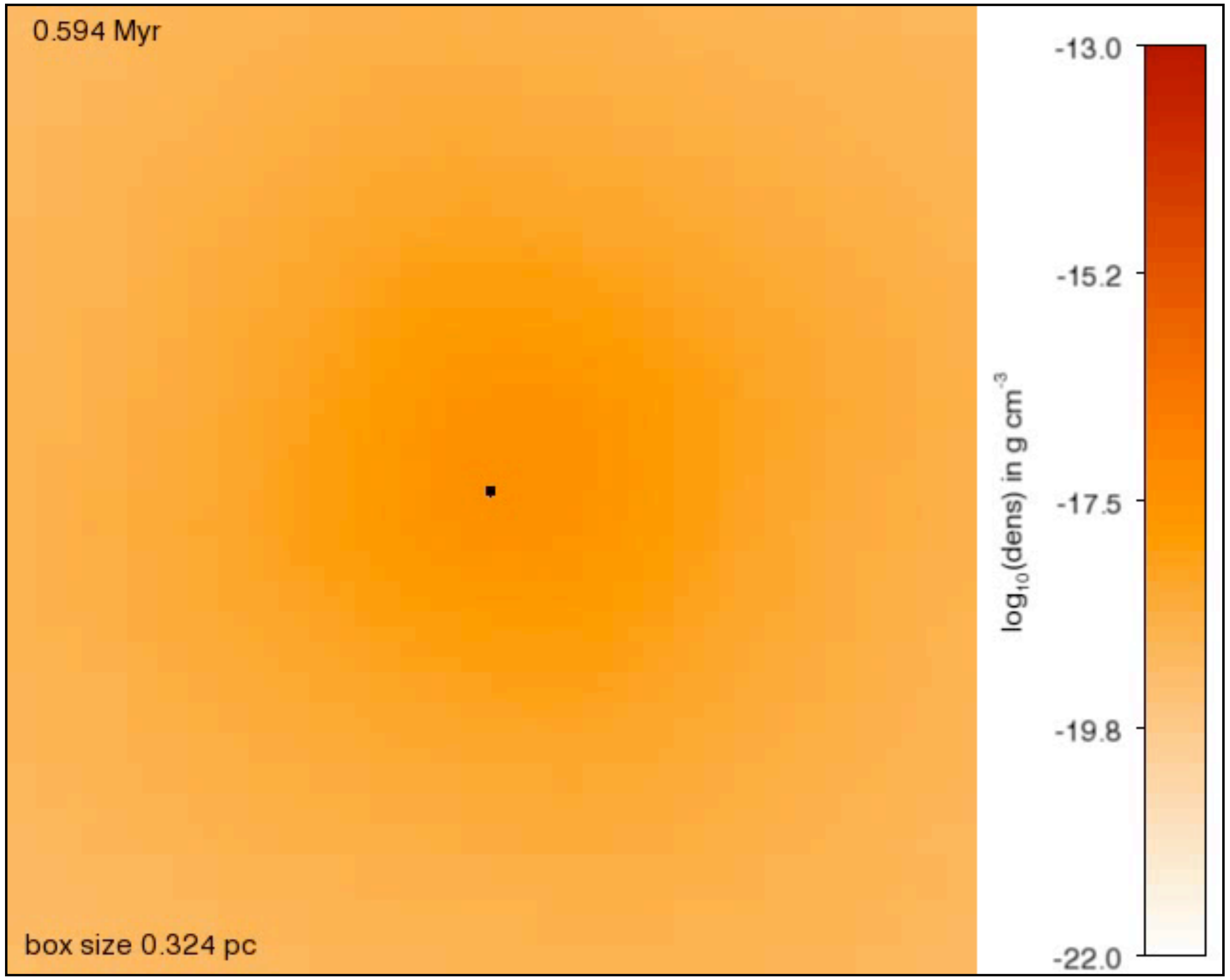
- massive core with $M_{core} = 1000\ M_{sol}$
- flat core with $r = 0.5$ pc and $\rho \sim r^{-1.5}$
- initial core rotation with $\beta = 0.05$
- accreting sink particles $\Rightarrow$ luminosity and temperature using ZAMS (*Paxton 2004*)
- highest grid resolution ~ 100 AU

Massive Star Formation: Dynamics of HII Regions

Simulations by Thomas Peters (ITA)



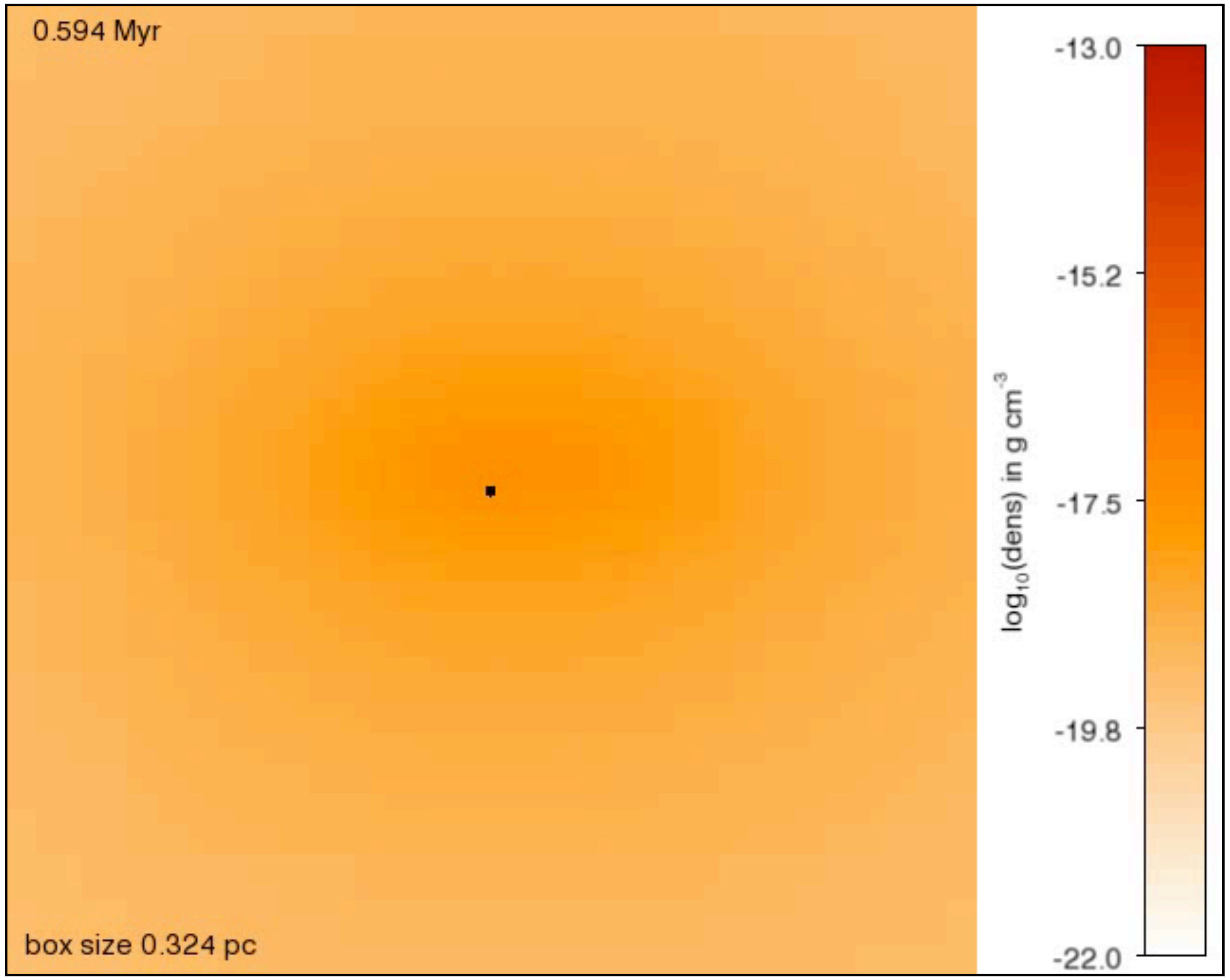
Disk edge on



Disk plane

Massive Star Formation: Dynamics of HII Regions

Simulations by Thomas Peters (ITA)



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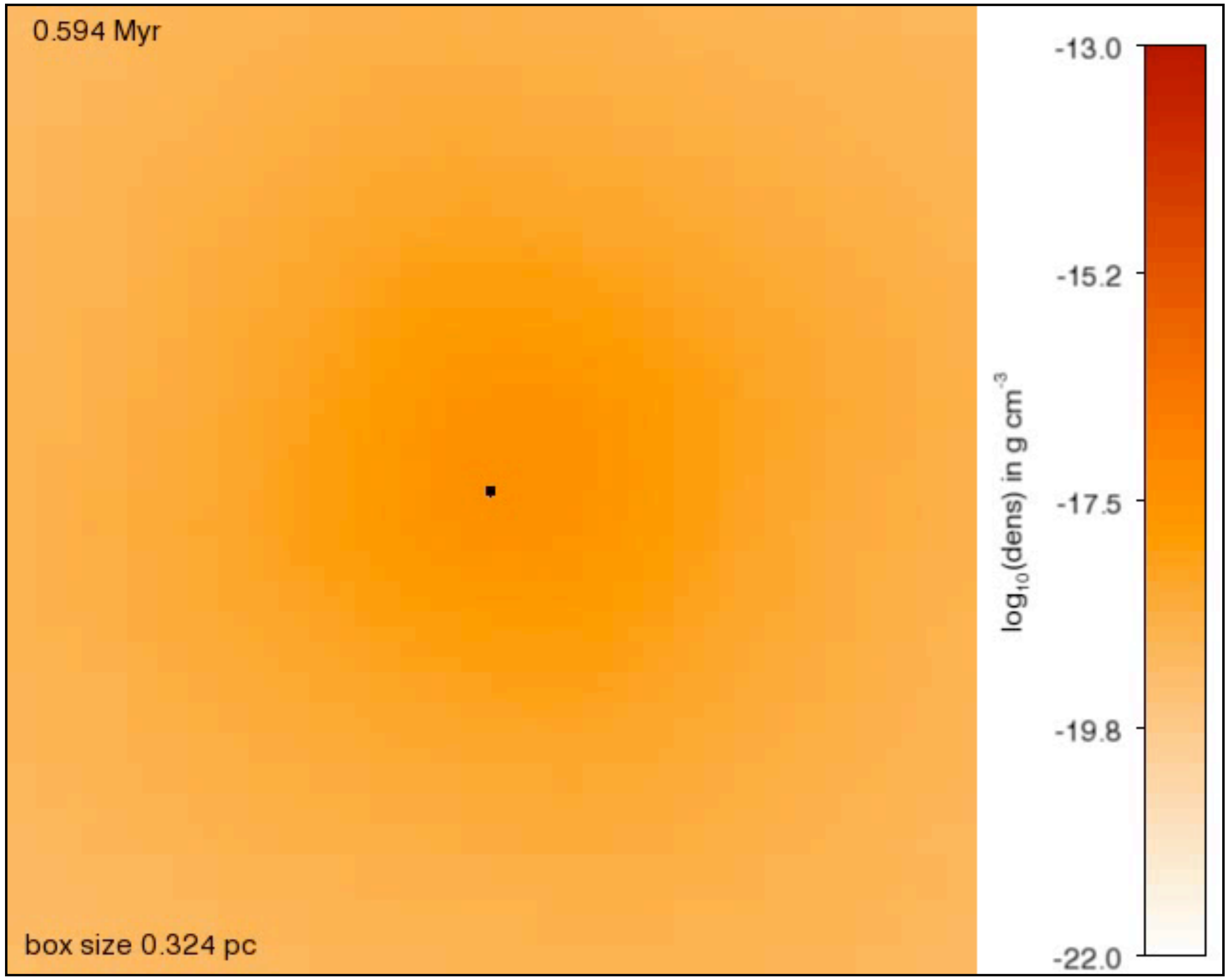
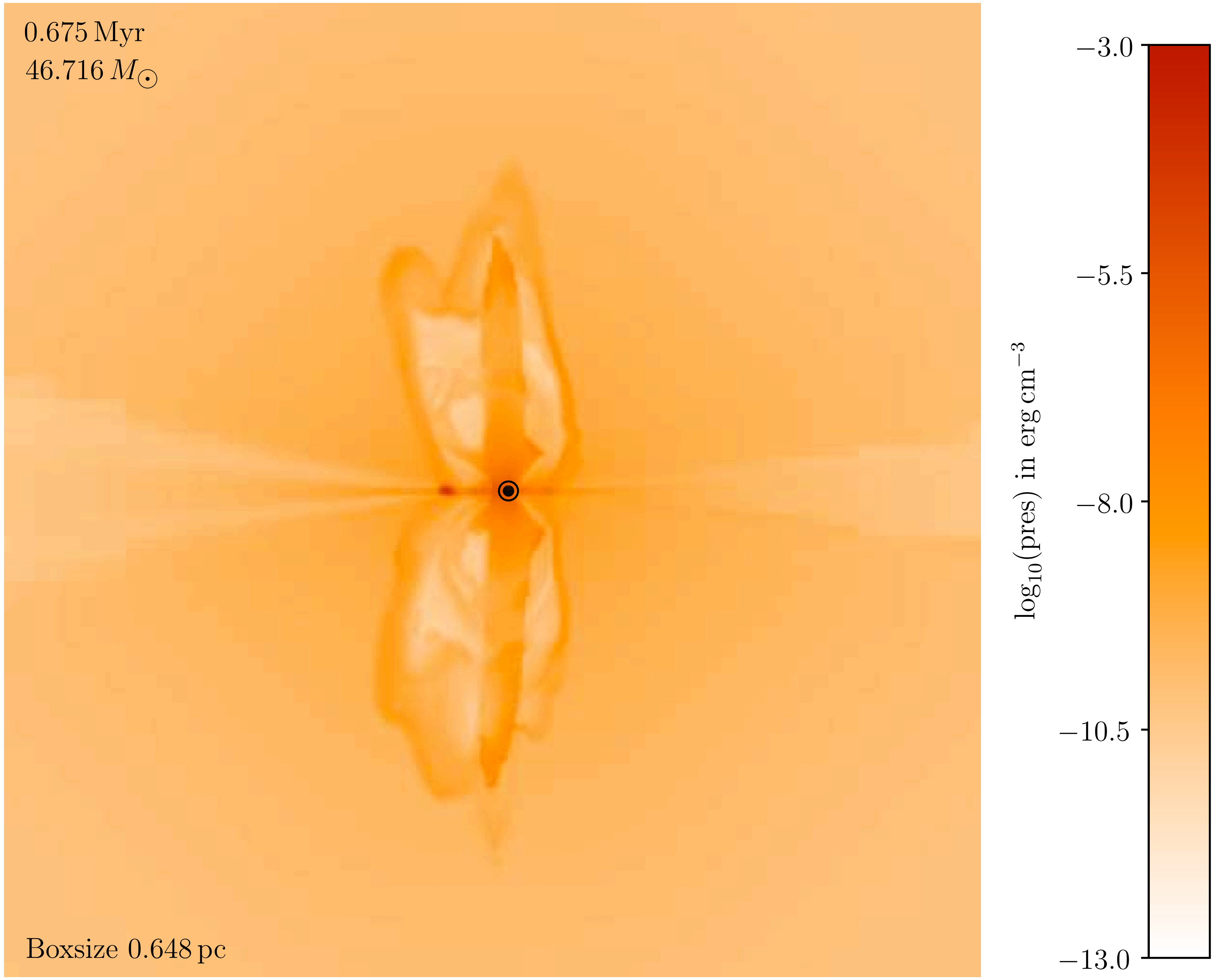


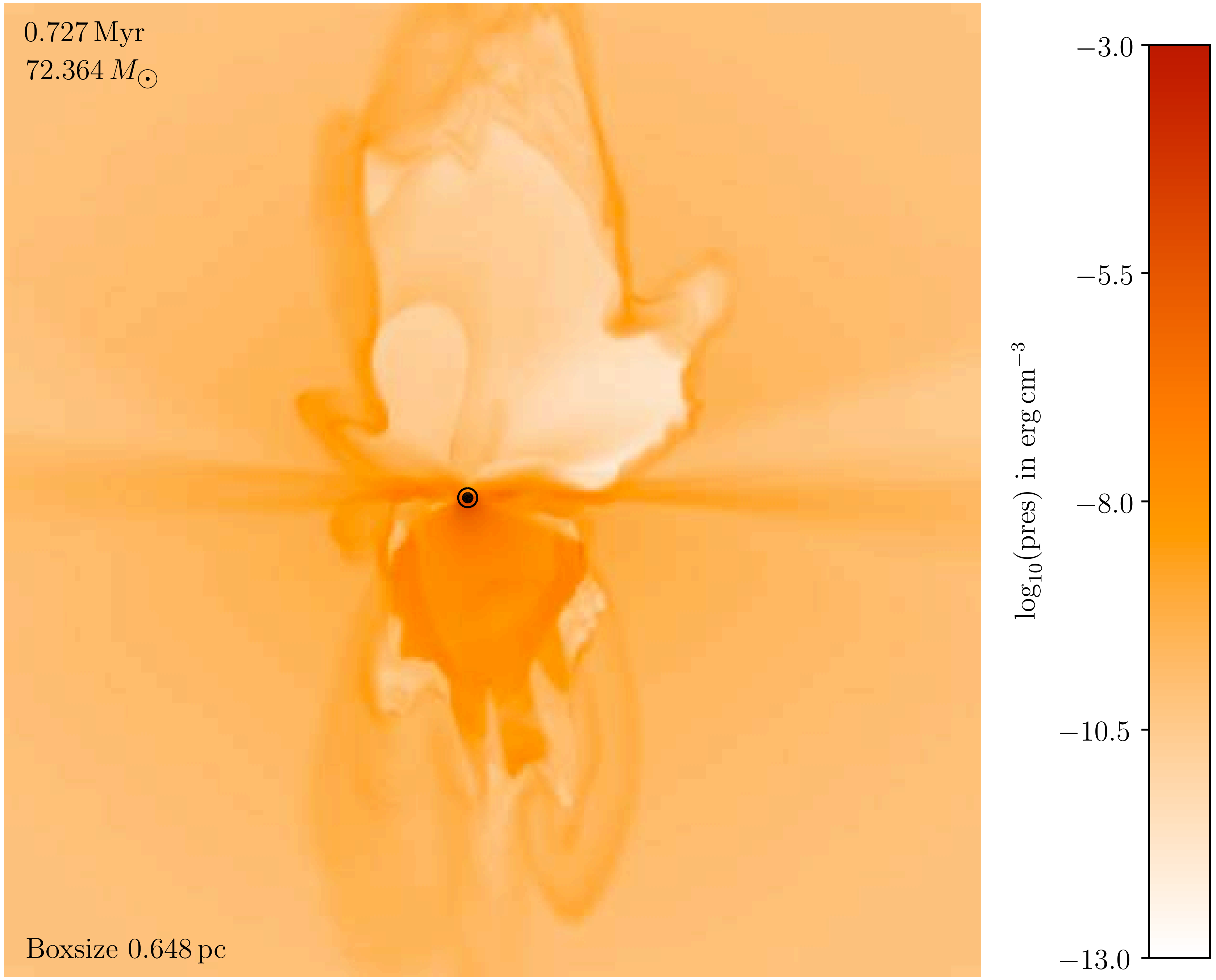
Disk plane

Dynamics of the H II Region and Outflow



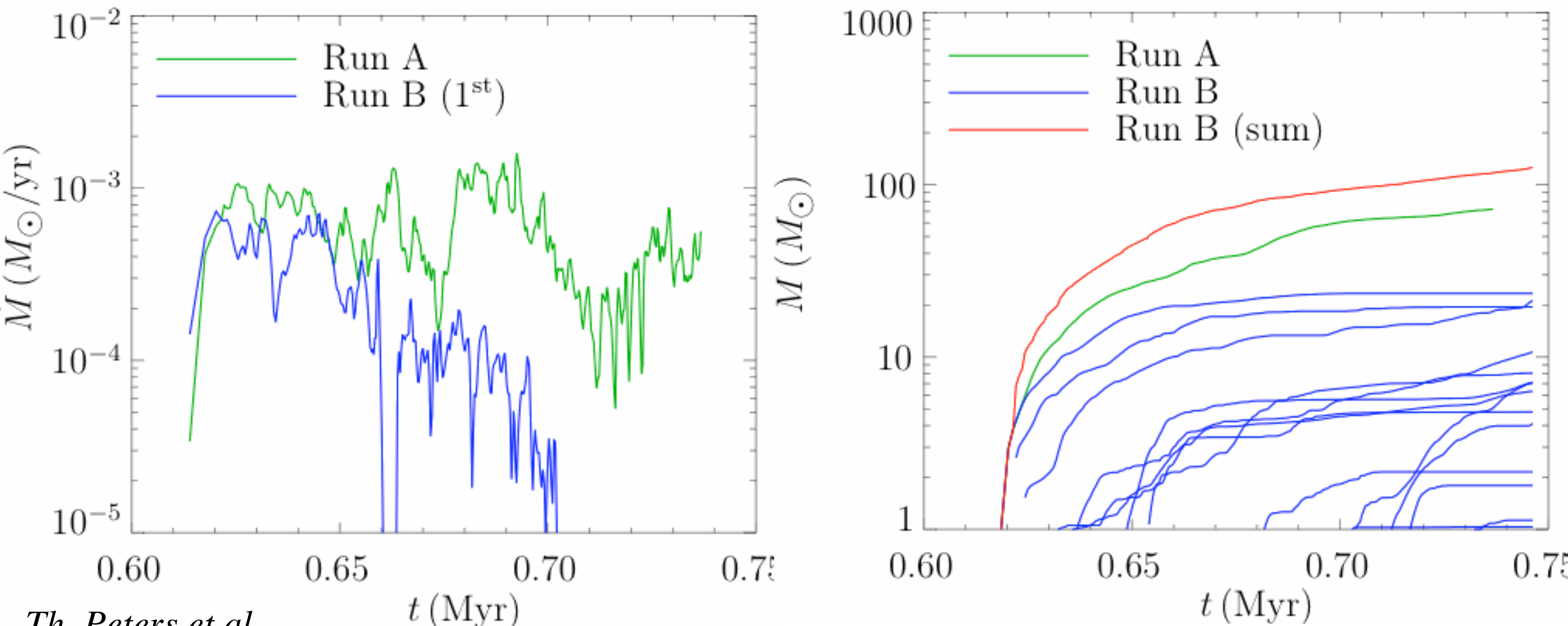
- ionization drives bipolar outflow
- pressure-driven expansion of shell
- thin-shell instability leads to fingers

Dynamics of the H II Region and Outflow



- size and morphology of H II region is highly variable
- cometary H II region totally reverses within less than $10\,\mathrm{kyr}$
- changes like this have been observed!

Multiple protostars: Dynamics of the H II Region

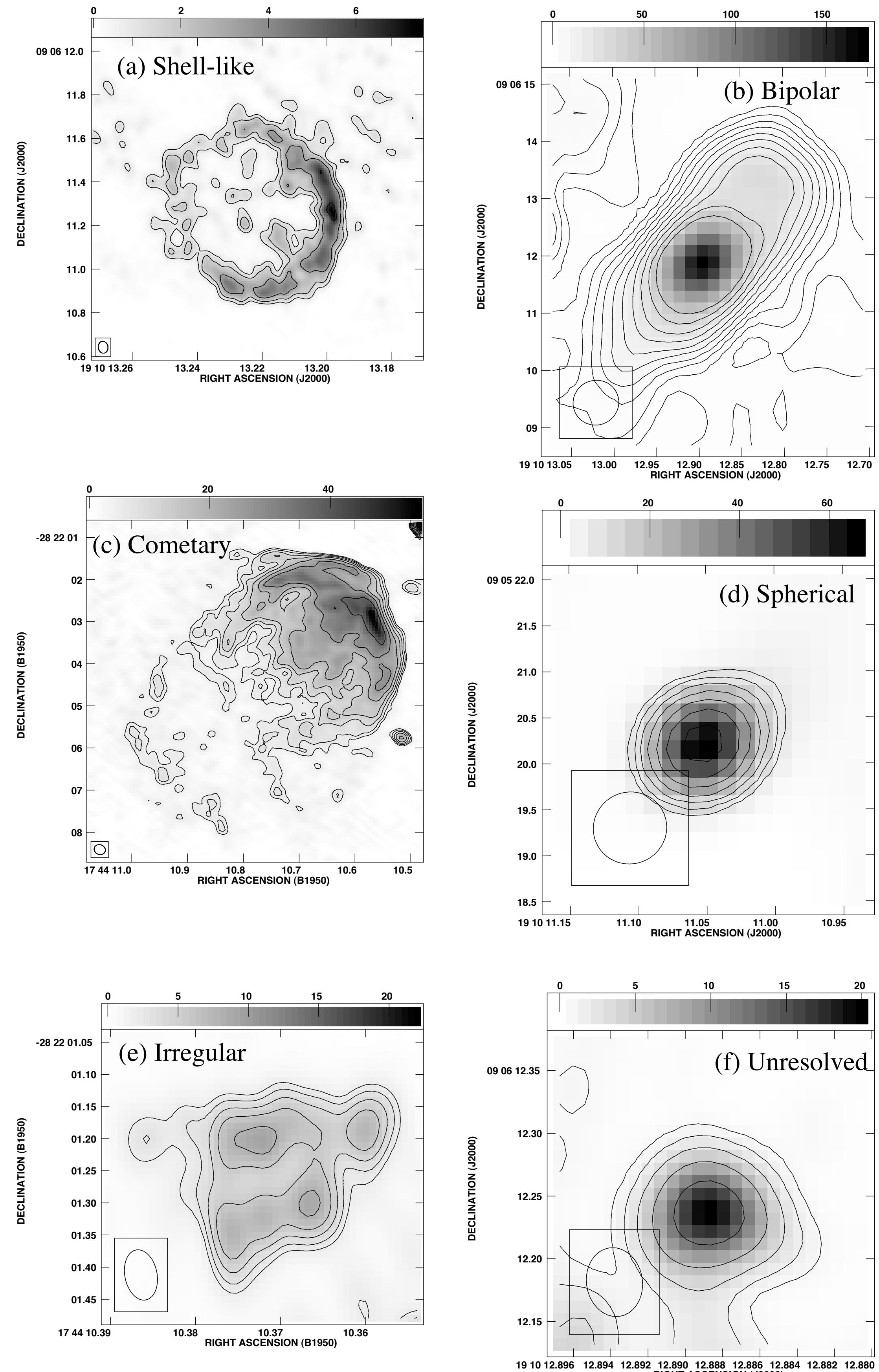


Th. Peters et al.

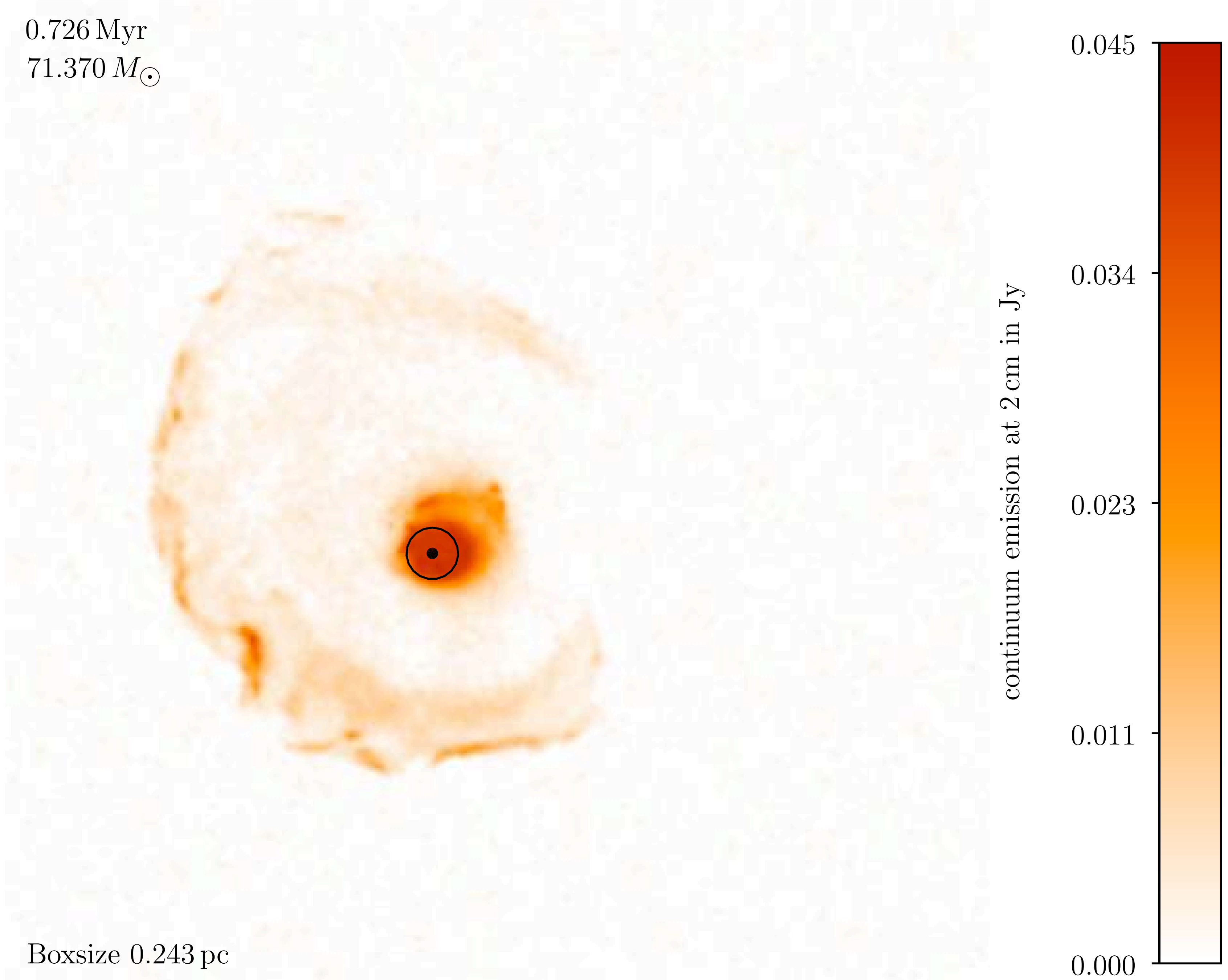
- ionization feedback does **not** shut off accretion
- **fragmentation**-induced starvation
- massive stars form in cluster

Classification of UC H II Regions

- comparison with De Pree et al. 2005 classification of UC H II regions in W49A and Sagittarius B2
- "irregular" is any resolved region which does fall into one of the other categories

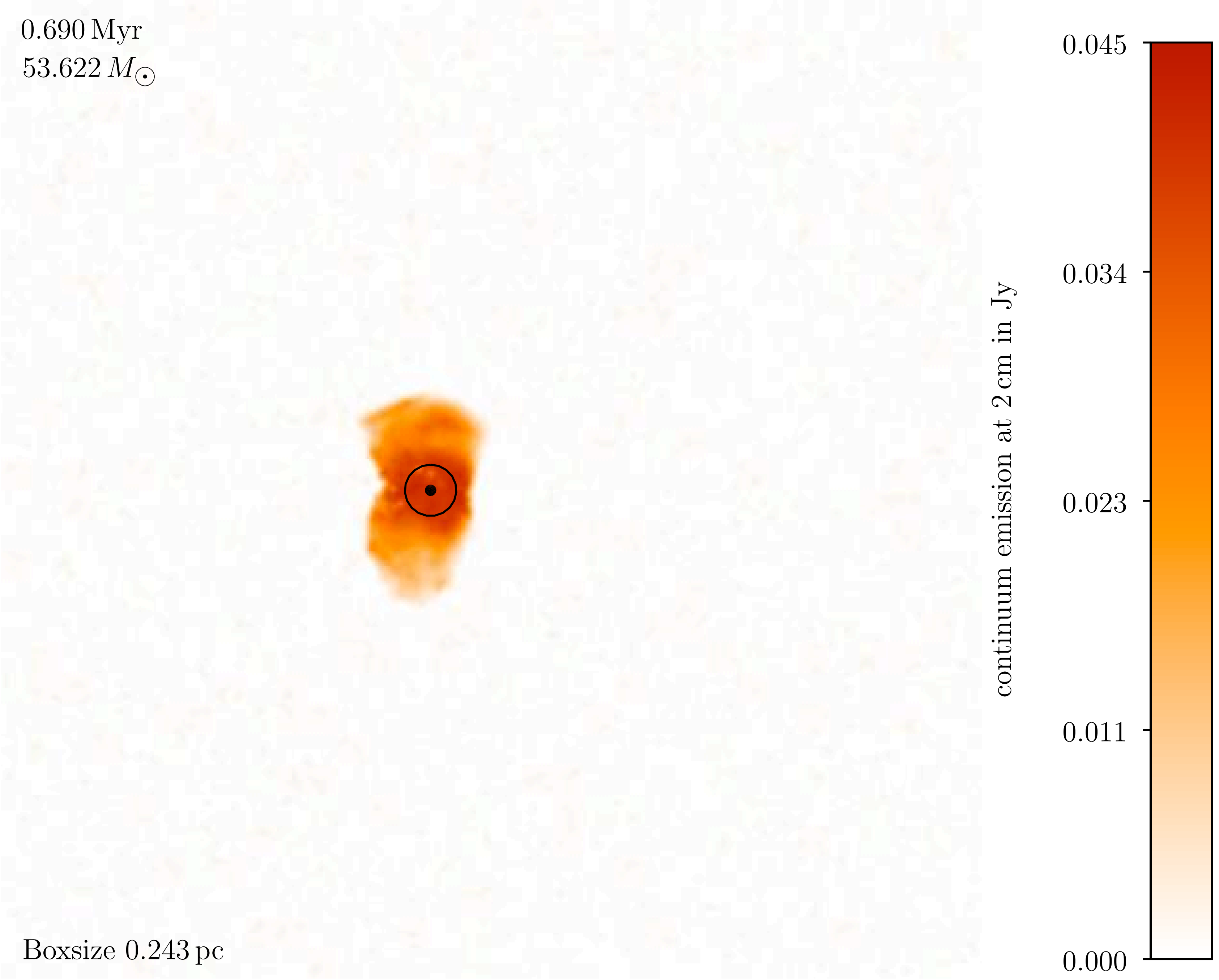


H II Region Morphologies



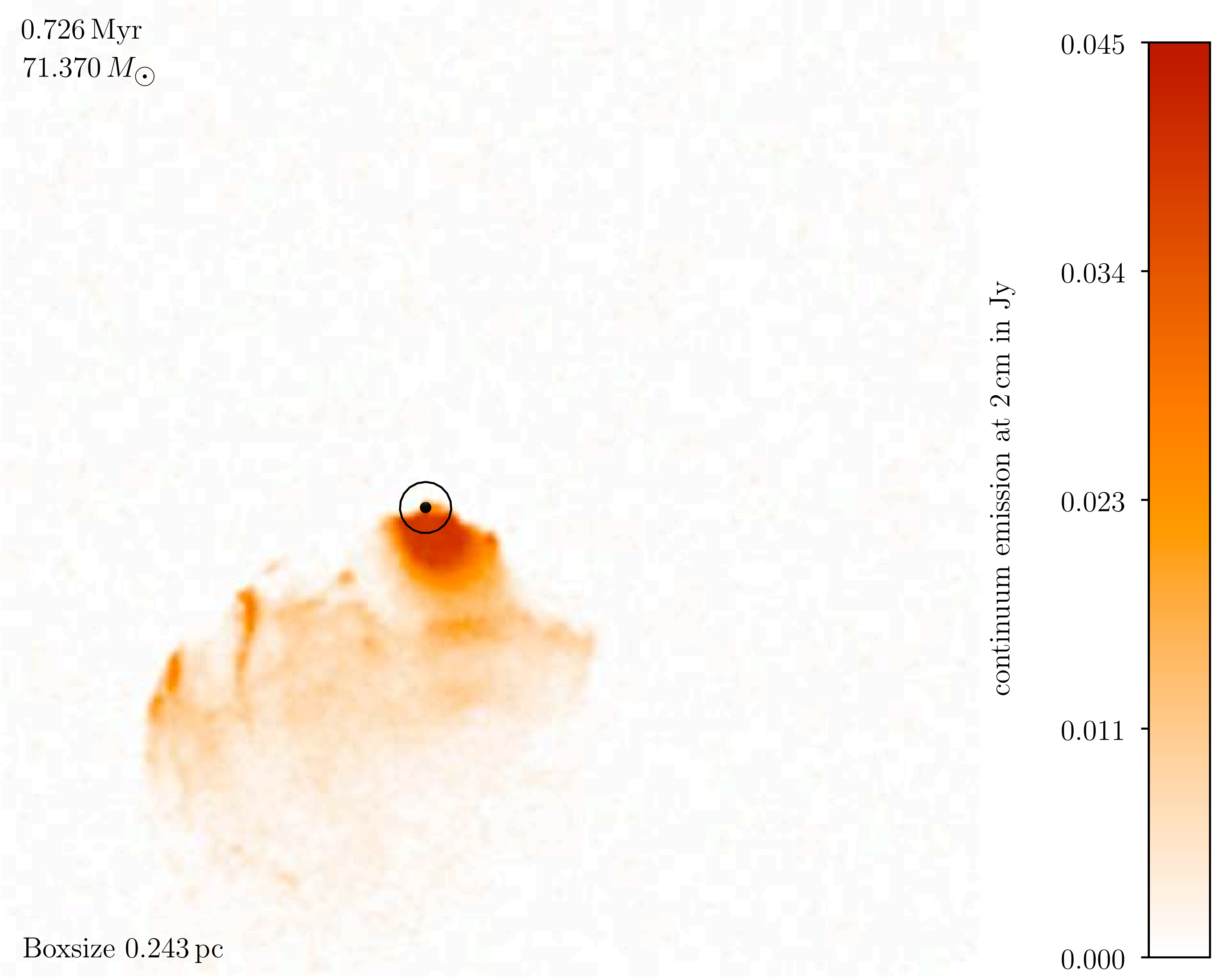
shell-like morphology

H II Region Morphologies



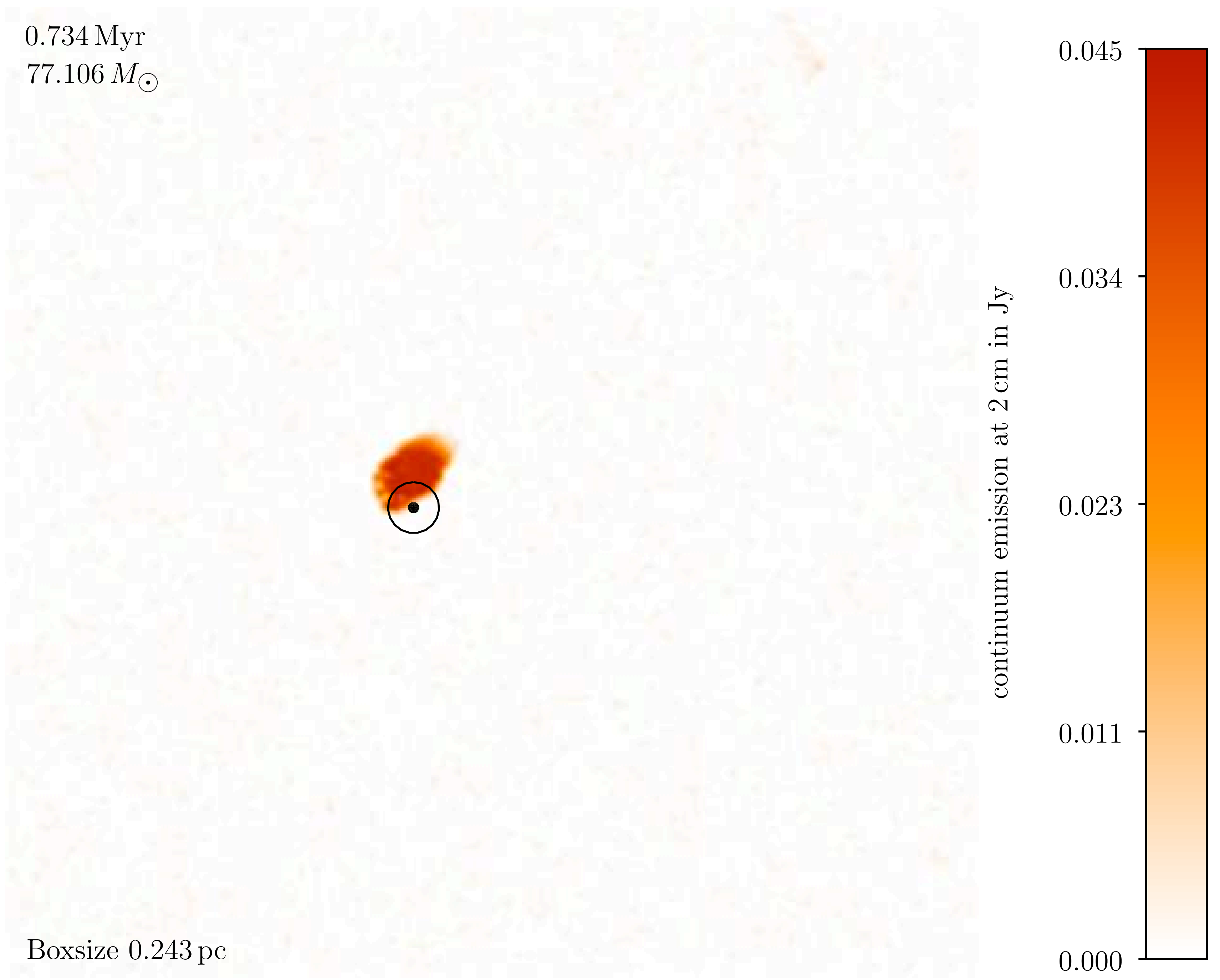
bipolar morphology

H II Region Morphologies



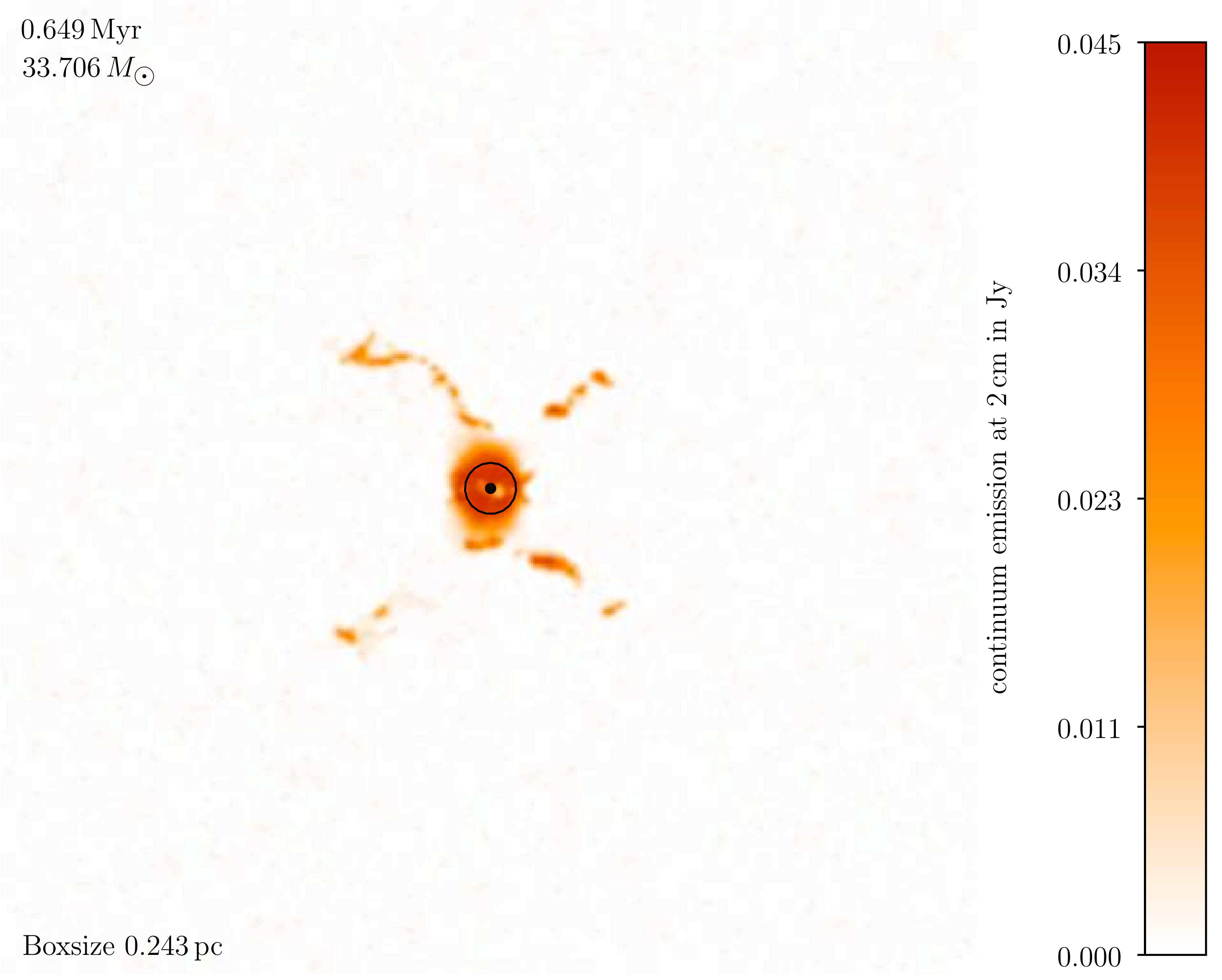
cometary morphology

H II Region Morphologies



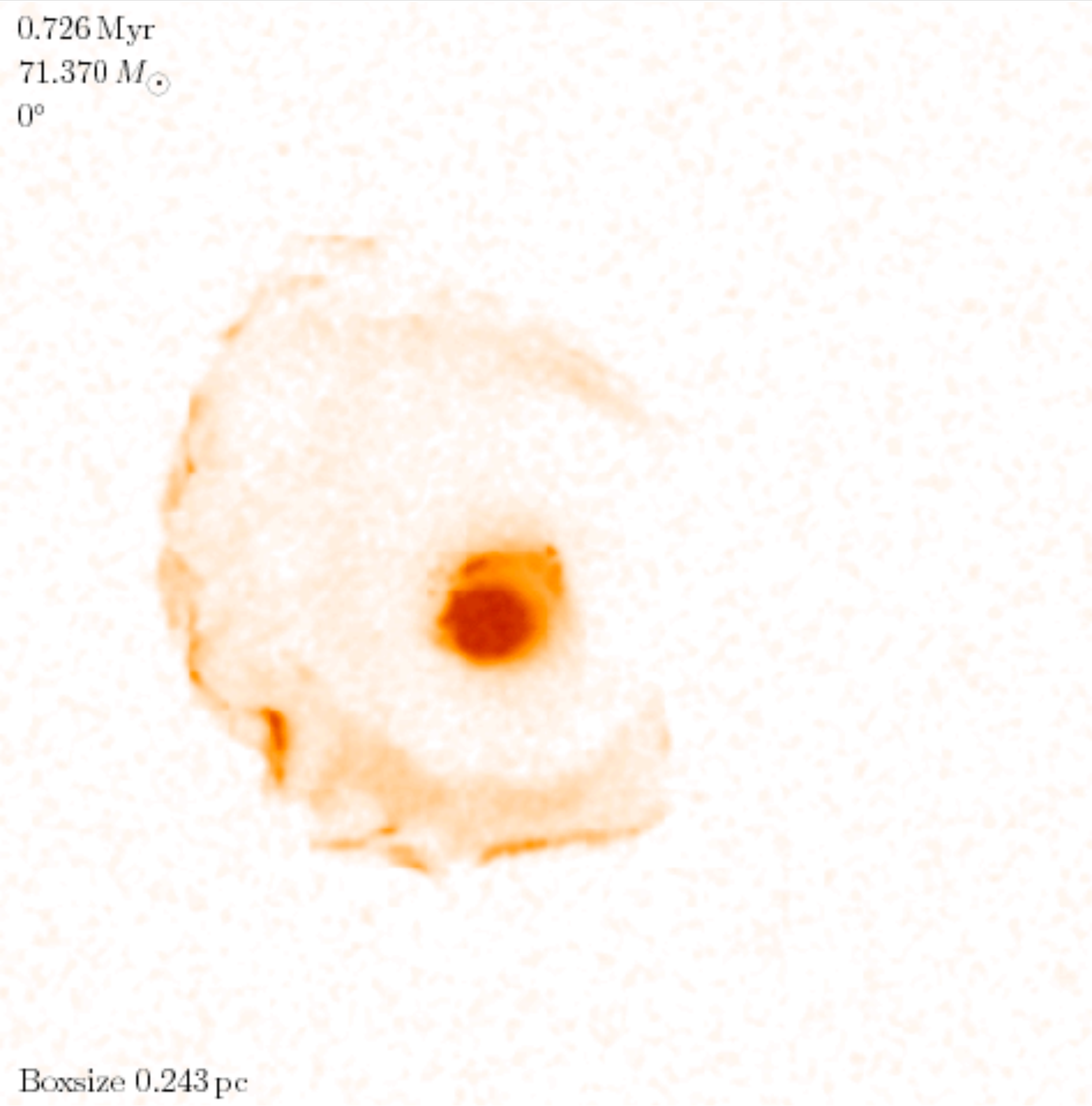
spherical morphology

H II Region Morphologies



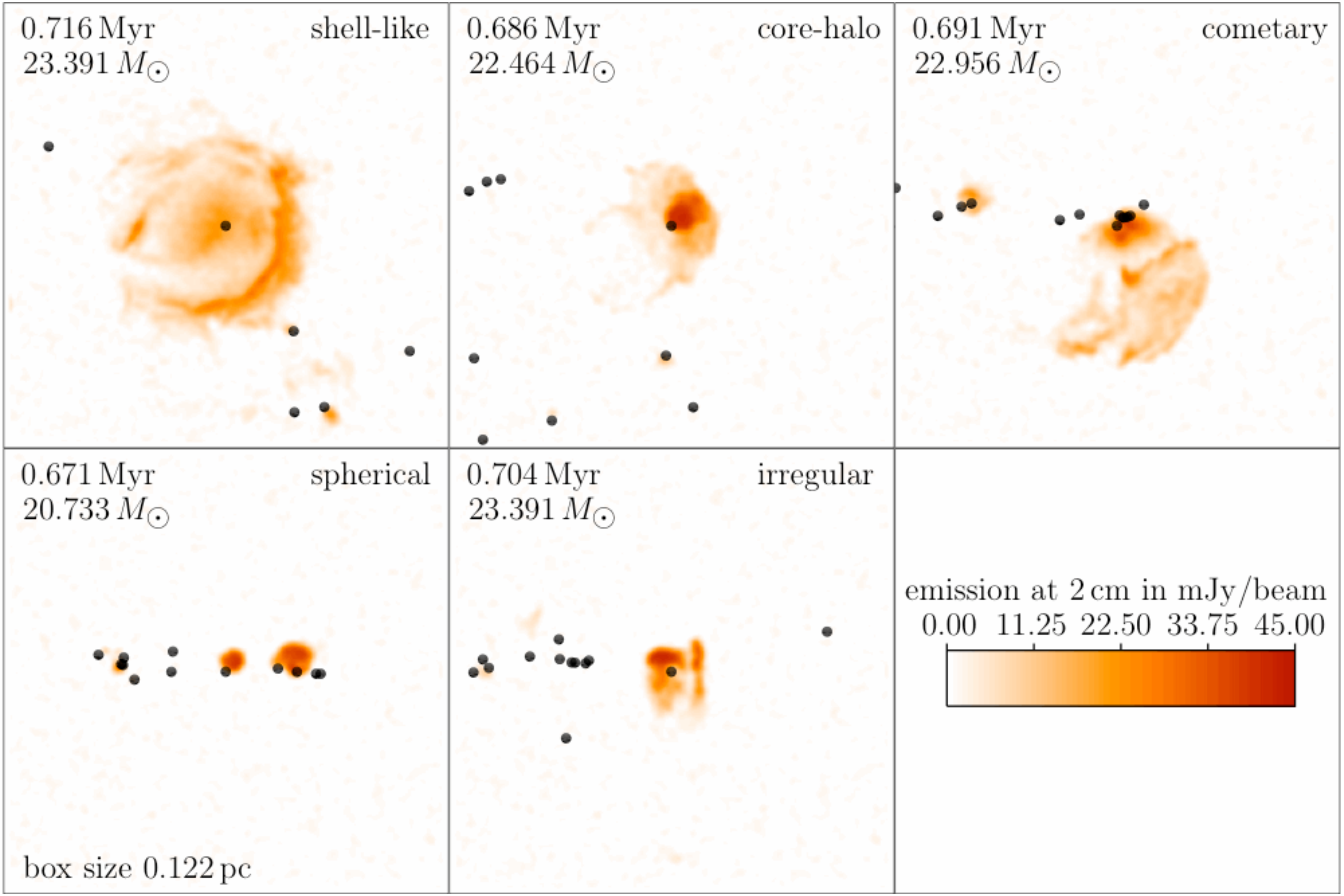
irregular morphology

H II Region Morphologies

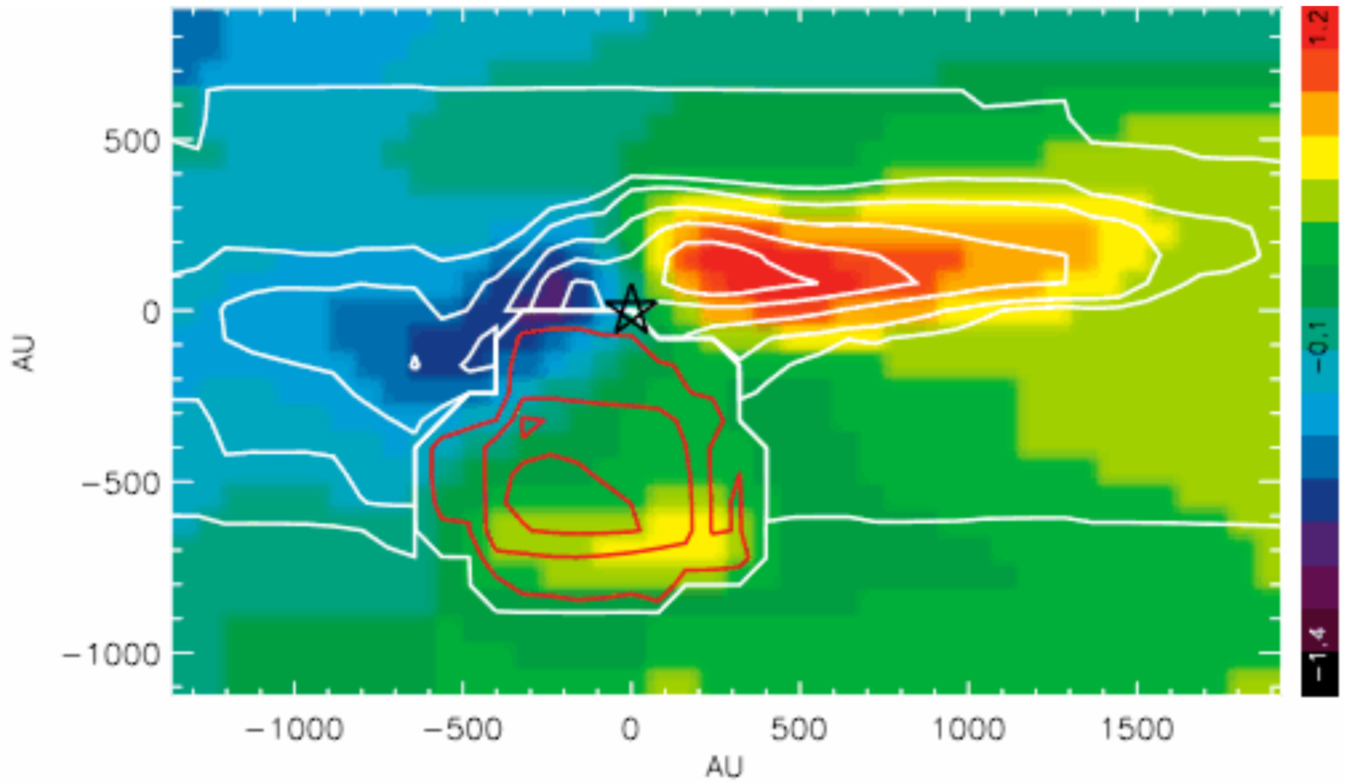


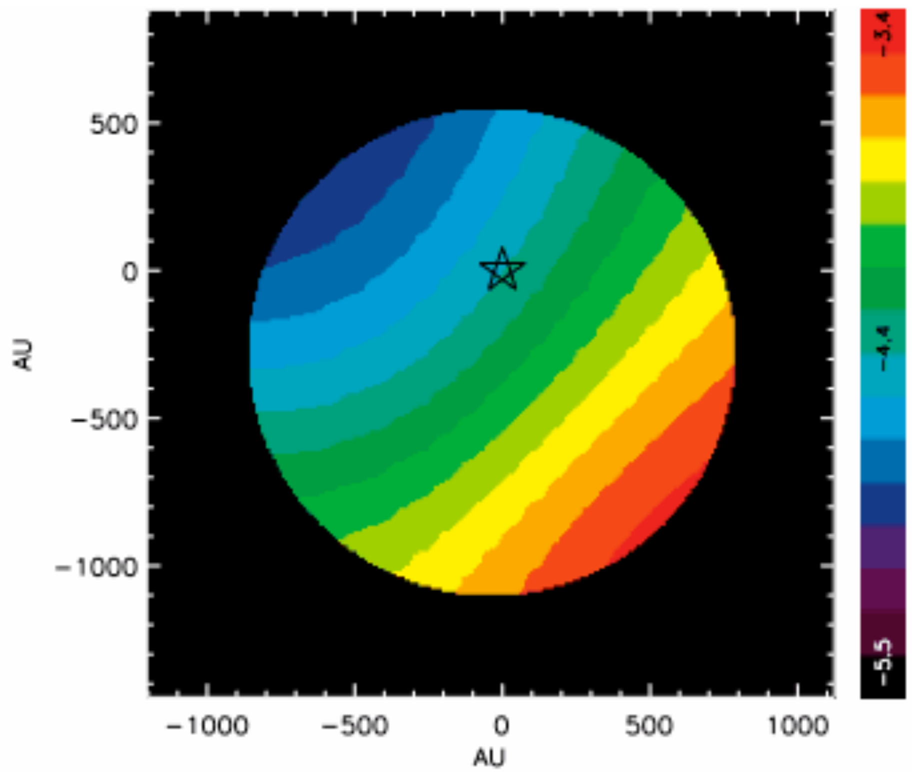
Morphology of HII region depends on viewing angle

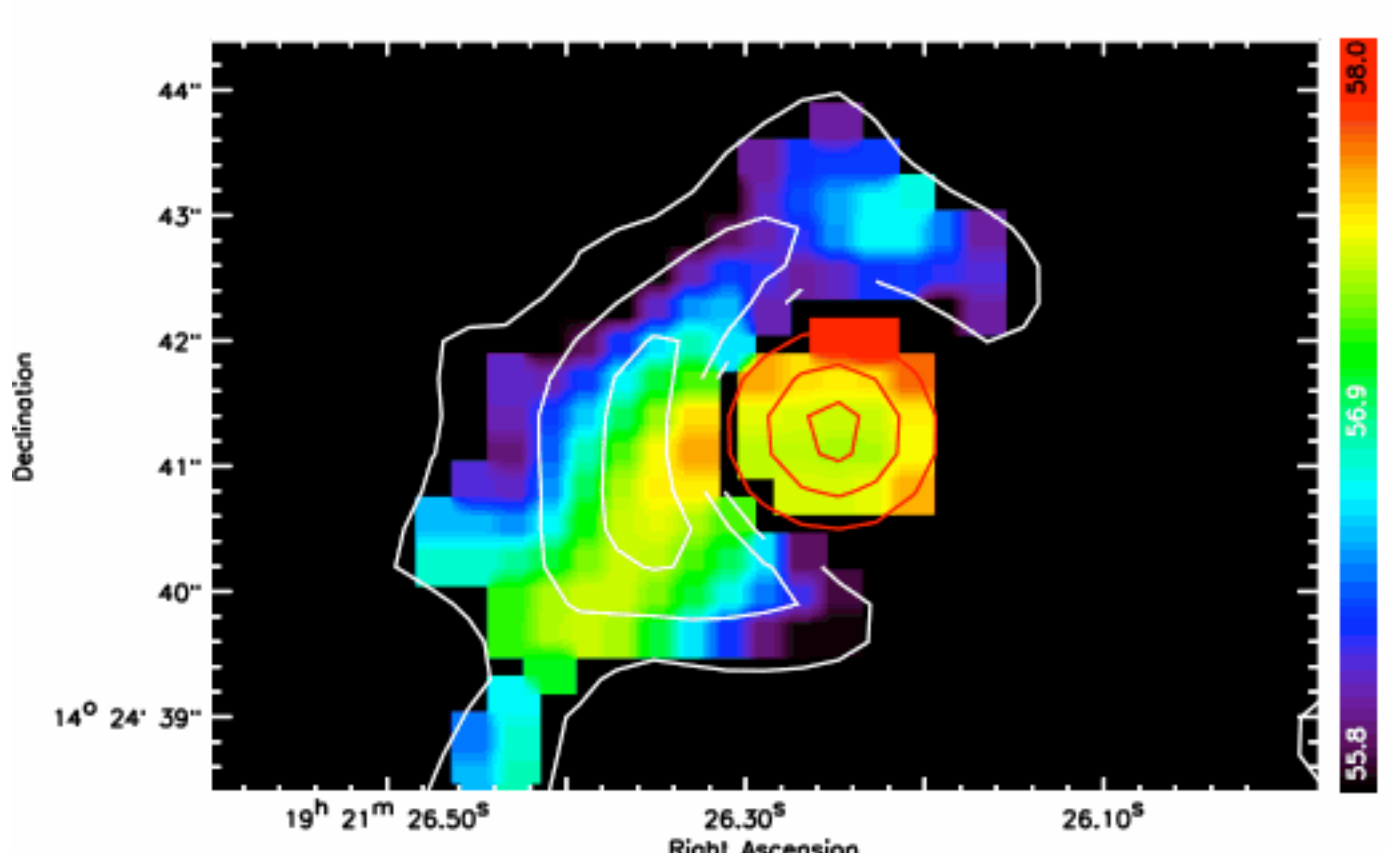
H II Region Morphologies

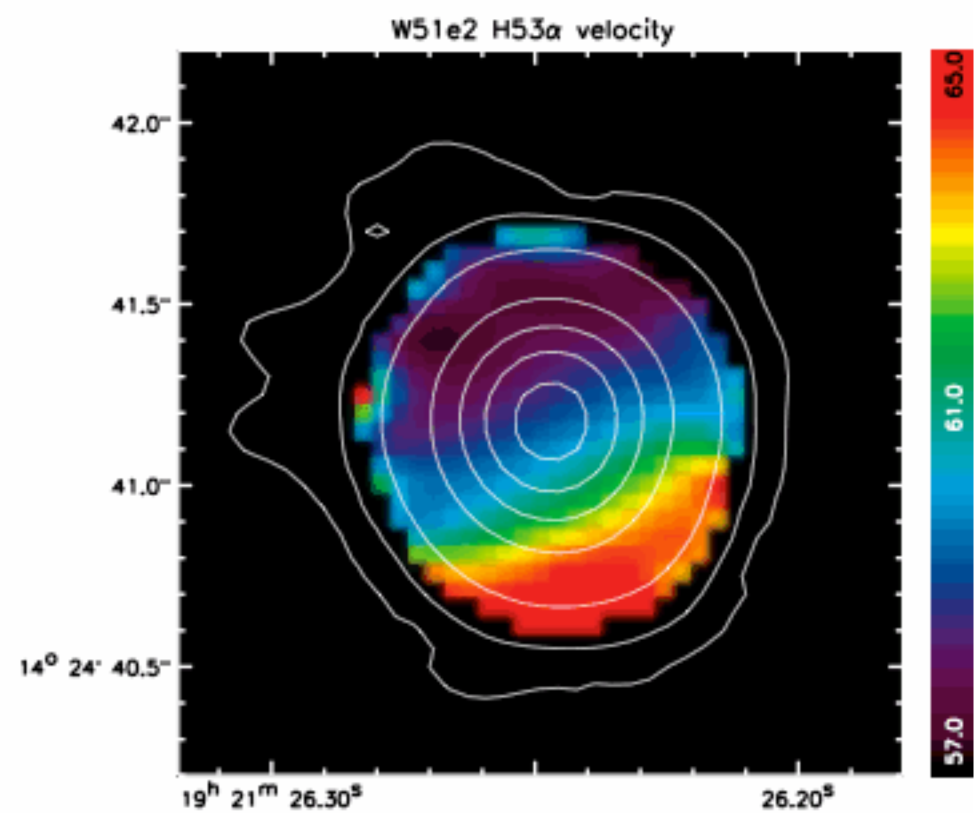


Comparison with observations: W51e2









data from *Zhang et al. 1998*

Keto & Klaassen 2008

Conclusions

- Molecular clouds can form at the cross section of **converging** flows by thermal instability
- MCs are **dynamic** objects with no distinct boundaries where warm and cold gas co-exist
- Ambipolar diffusion has only **little** influence on star formation
- Regions of **massive** star formation: rapid accretion through dense, unstable flows
- Ionization feedback does **not** shut off accretion
- HII regions are highly **variable** in time and shape
- All classified morphologies are seen in one run
- HII region will be gravitationally trapped (resolves lifetime problem, *Keto 2003*)